A STUDY OF THE FEASIBILITY OF SURFACE WATER HEAT PUMP SYSTEMS IN OFFICE BUILDINGS NEAR THE THAMES

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Energy consumption for air-conditioning in the commercial sector is rapidly growing in all developed countries at present. This is due mostly to the large floor space used by office buildings, the increased frequency of warmer summers, as a result of climate change and the continuous demand for high levels of thermal comfort by occupants. One way of reducing this energy consumption and the associated carbon emissions is to use heat pumps for cooling and heating, connected to a source of surface water, which can be used as a heat source or sink depending on the building's demands.

Given the large number of new office developments adjacent to both banks of the Thames in London, this study investigates the feasibility of using the water of the River Thames as a heat source or/and sink for a water loop heat pump (WLHP) system. The aim of this project was to investigate the possibility, the restrictions and the potential benefits of implementing such a system.

The first step was to collect data concerning the quality of the river's water as well as data on the thermal behaviour of the river and how it responded to London's climatic conditions. The study then used computer simulation to examine the energy performance of four different heating and cooling systems of a typical office building; a VAV central air-conditioning system, a WLHP system, an open-loop surface water heat pump (SWHP) system and a closed-loop SWHP system.

Results of the study showed that the most feasible system in the case of the Thames is a closed- loop SWHP system due to the quality of the river's water as well as environmental restrictions that emerged from the Water Resources Regulations. The system achieves an overall reduction of approximately 50% in energy consumption and CO_2 emissions compared to a VAV central system and a reduction of more than 10% compared to a conventional WLHP system. These figures reveal that the use of such a system in office buildings near the Thames is indeed an energy efficient solution which is worth considering.

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Additionally, I would like to thank Jeff Hirsch and my supervisors Dr. Alan Young and Dr. Ben Croxford for their useful advice.

ACH: Air Changes per Hour

DX: Direct Expansion

EEM: Energy Efficiency Measure

EES: Earth Energy Systems

EIA: Environmental Impact Assessment

GSHP: Ground- source Heat Pump

HVAC: Heating Ventilation Air- Conditioning

SWHP: Surface- water Heat Pump

UV: Ultraviolet

VAV: Variable Air Volume

WLHP: Water- loop Heat Pump

WSHP: Water- source Heat Pump

1. OVERVIEW

1.1 Introduction

The most important issues of our times are perhaps global warming and the availability of energy resources, therefore the efficient use of energy is vital for conserving fossil fuels and reducing pollutant air emissions. It has been estimated that the building sector is responsible for approximately half of the energy consumed globally, if embodied and operation energy are taken into account.

Energy consumption in the service sector (office buildings etc) is rapidly growing due for one reason to the expansion of the floor space as offices, for example, occupy almost twice as much floor space in 1994 as in 1970[1]. Additionally, increasing demands regarding thermal comfort in offices have led to the development of air-conditioned buildings with a particularly high electricity consumption resulting in high CO2 emissions.

Taking into consideration UK's moderate climate, it would be assumed that energy used for cooling accounts for only low proportion of the overall energy consumed in buildings. The fact is that by the end of 1994 approximately 10% of the floor area of commercial buildings (offices and retail premises) was air- conditioned and virtually no housing2. Figures though are beginning to rise rapidly and it is estimated that by 2015, sales of air conditioning units will increase dramatically[3].

The possibility that an increase of 1°C in average temperature will occur over the next two decades combined with the fact that it will lead to an increase of the cooling degree- days by 50-60% around the UK[4], reveal a new tendency regarding future cooling demands. Taking into consideration that people are beginning to adopt more and more in artificially cooled spaces (cars, public buildings etc) and their requirements for thermal comfort during the summer are becoming less tolerant, it is obvious that cooling needs are going to increase significantly.

Taking the above into consideration, it is obvious that reducing energy consumed in office buildings not only for space heating but for cooling as well, would lead to

[1] Pout C.H., Moss S.A. and Davidson P.J. (1998) Non-Domestic Building Energy Fact File.
[2] According to surveys carried out for BRE.
[3] BSRIA Report 79570/1: Future Market Potential for small Scale Air Conditioning in the UK (1998).
[4] CIBSE: Guidance on Outside Design Criteria, Air Conditioning (2000).

significant energy savings. The use of an appropriate and energy efficient HVAC system is an important step towards that direction.

1.2 The Concept of the Heat Pump

Heat pump technology is considered to be energy efficient since heat is not actually being produced (by combusting gas or using electricity) but transferred. Heat pumps in general have been widely used for decades. Refrigerators and air conditioners are common examples of heat pumps. A heat pump is an electrical device that extracts heat from one place and transfers it to another. Figure 1.1 represents the basic heat pump cycle.

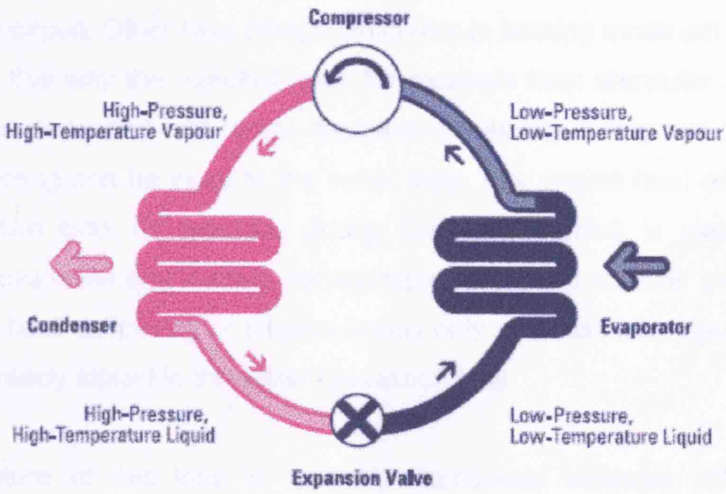


Figure 1.1: Basic Heat Pump Cycle[1]

Heat is transferred by circulating a substance called a refrigerant through a cycle of alternating evaporation and condensation. A compressor pumps the refrigerant between two heat exchanger coils. In one coil, the refrigerant is evaporated at low pressure and absorbs heat from its surroundings. The refrigerant is then compressed en route to the other coil, where it condenses at high pressure. At this point, it releases the heat it absorbed earlier in the cycle. The cycle described above is completely reversible thus heat pumps can operate both in cooling and heating mode.

[1] Heating and cooling with a heat pump: Natural Resources Canada/Energy Publications (2000).

1.3 Water-Loop Heat Pump Systems

A Water-Loop Heat Pump (WLHP) system is a heating and cooling system that places heat pumps in each building zone while the heat pumps are connected with a re-circulating two-pipe distribution system. The piping system adds or removes heat to the circulating water. WLHP systems are best applied to buildings where there is often a requirement for simultaneous heating and cooling in different parts of the building.

Heat pumps operating in cooling mode will extract heat from the room and deposit it into the water circuit. Other heat pumps which are in heating mode will take heat from the circuit. In this way the rejected heat, for example from computer rooms, can be recovered and deposited into rooms demanding heating. If it is required, additional heating or cooling can be input to the water loop. Any overall heat deficiency in the water circulation loop, for example during the winter period, is met by heat from external sources while any surplus, for example during the summer period has to be rejected. The heat deficiency or surplus facility only operates when demand exceeds the energy already stored in the water circulation loop.

The temperature of this loop is typically maintained between 16°C and 32°C. Conventional WLHPs use cooling towers to remove heat from the loop temperature when it exceeds 32°C and heat is added with a boiler if the temperature falls below 16°C.

The most favourable type of building for the use of WLHP systems is in general commercial buildings and office buildings in particular. This is due to the fact that office buildings with a core- perimeter layout take advantage of the heat pumps' loop ability to transfer heat from the core to the perimeter zones where it is required, thus simultaneously cooling the core and heating the perimeter spaces. Even during the heating period, the cooling requirement of an office building in its core spaces may exceed the actual heating requirement due to the high lighting and internal loads.

Other heating/cooling systems that use heat pump technology as well are the following:

- Central heating/cooling system with two-pipe distribution system and fan-coil units: In this system one ore more large heat pumps can be used to cool or heat water which is then directed to a two- pipe distribution system and supplies fan-coil units. This system though cannot cool and heat simultaneously since it is based on a two pipe distribution system.

- Central heating/cooling system with four-pipe distribution system and fan-coil units: In this system heating and cooling can be supplied simultaneously since supply and return piping exist on both the evaporator and the condenser of the heat pump(s).

The WLHP system and the central system with four-pipe distribution system can therefore ensure the occupants' thermal comfort since they provide year-round heating and cooling.

The central systems in general have the advantage of smaller installed capacity comparing to distributed systems such as the WLHP system. This is due to the fact that individual heat pumps must be sized for each zone's peak load while central systems are sized so as to handle the overall peak load of the building. Total capital cost of the system though is not necessarily less, taking into account the piping cost.

On the other hand, central systems require more space since the large heat pumps will have to be installed in a separate mechanical equipment room while the distributed heat pumps can be located in the ceiling plenum space. Additionally, maintaining a distributed heat pump system does not cause issues as equipment shut down since there is only a local impact in the zone involved. Maintenance of a distributed heat pump system is also more economical.

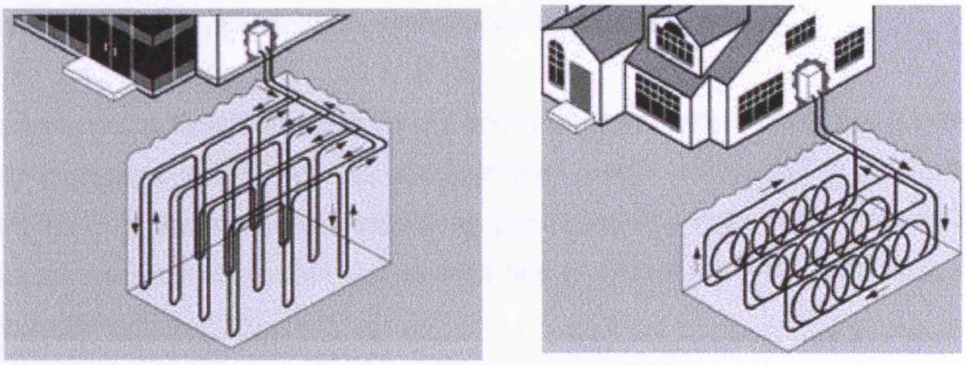
Taking all of the above into consideration, in the case of office buildings demanding both heating and cooling simultaneously, a WLHP system seems an energy efficient strategy.

1.4 Earth Energy Systems

Earth Energy Systems (EES) is a technology oriented towards minimising energy consumption using the earth or ground/surface water as a source of heat during the winter period and as a "sink" for the removed heat during the summer period.

Examples are:

• Ground-coupled heat pumps, which use the ground as a heat source and sink either with vertical (figure 1.2) or horizontal ground heat exchangers (figure 1.3).



Figures 1.2 and 1.3: Vertical and horizontal ground-coupled heat pump systems (Source: www.nemmar.com)

• Ground-water heat pumps (figure 1.4), which use underground (aquifer) water as a heat source and sink.

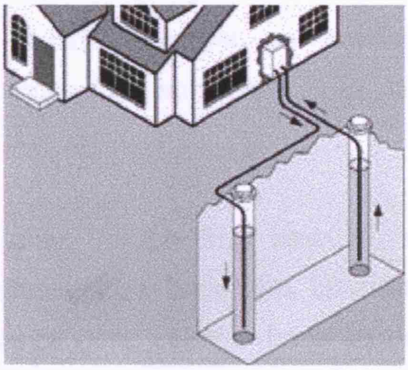


Figure 1.4: Ground- water heat pump system (Source: www.nemmar.com)

• Surface-water heat pumps (figure 1.5), which use surface-water bodies (lakes, rivers etc.) as a heat source and sink and will be thoroughly analysed in the following chapter.

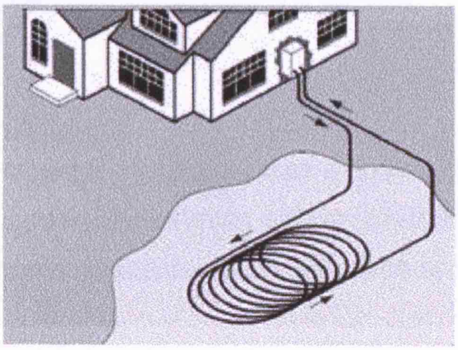


Figure 1.5: Surface- water heat pump system (Source: www.nemmar.com)

Ambient air is free and widely available, and it is currently the most common heat source for heat pumps. However, the capacity and performance of air-source heat pumps decrease rapidly with decreasing ambient temperature during heating season, and with increasing ambient temperature during cooling season.

Several benefits regarding the ground's and water's properties have raised interest in using them as a source instead, although their use is still limited. EES have been widely used in the seventies, especially ground source heat pumps, when the Oil Crisis awakened conservation awareness and launched interest in reducing energy consumption.

The rate of installation in Europe is increasing but generally the market growth has been slow ever since. In Britain the technology is still at a demonstration stage with a few hundreds of installations[1]. The capital cost of this short of installation followed by the low energy prices have not encouraged the awareness of this short of technology. Payback periods of EES, however, as reported from demonstration projects[2] which involved EES ranged from immediate to 12 years with an average of 5.2 years.

This is due to the fact that even though EES have an increased capital cost compared to conventional systems, they have less operational and maintenance costs. Regarding the maintenance cost, studies[3] have suggested 20%-30% lower costs with EES in general, due to the simplicity of the equipment and the less specialized skills needed in servicing the heat pumps over more complex chillers, boilers and VAV controls.

EES can be used in combination with the heating/cooling systems based on heat pump technology that were described in the previous section.

1.5 Hypothesis

As previously mentioned, river water can be used as a source or sink in EES. WLHP systems can potentially be used in combination with an Earth Energy System (EES) thus connected to a central pumping station and heat source or sink.

[1] Ground Source Heat Pumps Seminar: The National Energy Foundation, 2005.
[2] Doug Cane & Jeremy Garnet: Commercial/Institutional Heat Pump Systems in Cold Climates (2000).
[3] Natural Resources Canada/Energy Publications: Commercial Earth Energy Systems (2002).

In the case of a Surface Water Heat Pump (SWHP) system, for example, combined with a WLHP system, the boiler, the cooling tower, and the associated pump and heat exchanger have been replaced with the river loop system. The only remaining auxiliary is the loop circulation pump. Heat is added to or removed from the river at no cost and no energy is required to operate a boiler or a cooling tower.

The development of office buildings adjacent to both banks of the Thames in the London area is increasing and the idea of using the Thames' water as a source or sink for a WLHP system, thus in combination with a SWHP, is attractive due to the following reasons:

- The particular buildings are close to the river thus no long piping length is required.
- Relatively low capital cost due to reduced excavation and drilling costs compared to a ground source heat pump system.
- Low pumping energy requirements.
- Low maintenance requirements.
- Low operating cost.

1.6 Case Studies

Currently there only a few known applications of SWHP systems in the UK which are mostly small scale projects concerning residential buildings. Most applications worldwide are in Canada and the U.S. though there are certain applications in northern Europe as well.

In Toronto, for example, there is a large scale project aiming to provide cooling to high-rise buildings in the center of the city using water from the city's lake. The cooling system is based on three intake pipes situated deep in the lake where the cold lake water (approximately 4°C) is pumped to a filtration plant when it is treated until it achieves potable quality standards. After treatment in the filtration plant it passes through a closed loop absorbing heat from a separated chilled water loop. Since the loop is closed, the water's temperature rises up to 12.5 °C without loosing its potable quality and is then distributed in the city as tap water. The project is estimated to reduce energy consumption by 75%.

In the U.S. there is a similar project developing in Arkansas, where Arkansas' river water is being used in order to cool a building situated by its bank. The building is a five- story office building and uses plastic coils sunk in the river for cooling thus operating costs are limited to pumping and fans' operation only.

In Norway there is an extensive use of SWHP systems which use sea water. A typical example is a research center in Trondheim, a city located on the coast of Norway. The building has a water loop internal distribution system which is served by heat pumps. Seawater at a temperature range from 5°C to 6°C serves as the heat source for the heat pumps' evaporators. The discharge from these evaporators is then routed to a heat exchanger where it absorbs heat from the space cooling loop. Before finally discharging back to the sea, this fluid passes through another heat exchanger where any heat gained from the cooling loop can be transferred to the heating loop in case it is required. It should be noted that in this case as in most cases there is a downsized boiler as a back up heat source.

The particular system saved 8,280 GJ of thermal energy for heating (comparing to a conventional oil-fired heating system) and 0.4 GWh of electricity for cooling (comparing to a conventional central air-conditioning system). The payback period of this installation is reported to be 4.5 years.

As a final example, the government building in the city of Maastricht in Netherlands uses water from adjacent river Maas as both a heat source and a sink. The system has no back up heat source (as a boiler for example) and this is due to its particularly innovative heat pump.

The building has a water loop internal distribution system which is served by one heat pump, a high efficiency absorption pump that uses ammonia- water as fluid and incorporates a generator/absorber heat exchanger. This allows a temperature overlap that allows heat to be exchanged between the absorber and vapour generator thus optimally adjusts the process for a given temperature range. There are yet no publicised performance data for this system.

1.7 Aim

Taking the above into account, the aim of this project is to investigate the possibility, the restrictions and the potential benefits of implementing a SWHP system in combination with a WLHP system in office buildings near the banks of river Thames in the London area.

2. DESCRIPTION OF SWHP SYSTEMS

2.1 General Characteristics of SWHP Systems

Surface water heat pumps are considered by ASHRAE as a subset of ground source heat pumps due to their similarities in applications and installation methods. The term ground source heat pump (GSHP) in general is applied to a variety of systems that use the ground, groundwater or surface water as a heat source or sink. The thermal characteristics of surface water bodies though are significantly different from those of the ground.

A SWHP system is a viable and relatively low-cost EES option. When a building is near a pond, lake or river, submersing a series of coiled pipes beneath the surface will constitute the heat exchanger. This system requires minimum piping and excavation, but the pond or lake must be deep enough and must also have sufficient surface area to accommodate this type of system.

During the heating mode heat is removed from the water body (the lake or river) through a liquid, such as the water itself or an antifreeze solution, upgraded by the heat pump, and transferred to indoor air. During the cooling mode process is reversed: heat is extracted from indoor air and transferred to the water body directly through the water or through an antifreeze solution. A direct-expansion (DX) system uses refrigerant in the surface water-heat exchanger, instead of an antifreeze solution.

SWHP systems have in general two parts: a circuit of submerged piping outside the building, and a heat pump unit inside the building. Unlike the air-source heat pump, where one heat exchanger (and frequently the compressor) is located outside, the entire water source heat pump unit is located inside.

The submerged piping system of a SWHP system can be either an open- loop system or a closed- loop system.

2.2 Open-loop SWHP Systems

An open- loop system (figure 2.1) uses the heat retained in the body of water (in this case the river). The water is drawn up through a well directly to the heat exchanger, where its heat is extracted. The water is then discharged back to the river through a separate well. Entering river water temperature must remain above 5.5 °C to prevent freezing.

This process is often referred to as the "open discharge" method and since it may not be acceptable in certain areas, it needs to be approved by the local authorities in order to prevent the cause of environmental damage.

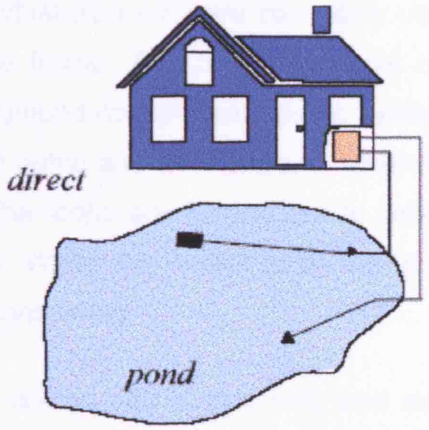


Figure 2.1: Open- loop system
(Source: Geo-heat Center, Oregon Institute of Technology)

2.3 Closed-loop SWHP Systems

Closed-loop systems (figure 2.2) collect heat from the river by means of a continuous loop of submerged piping. The medium is circulated through the inside of the tubing and heat is released to or absorbed from the river. No water enters the system from the river.

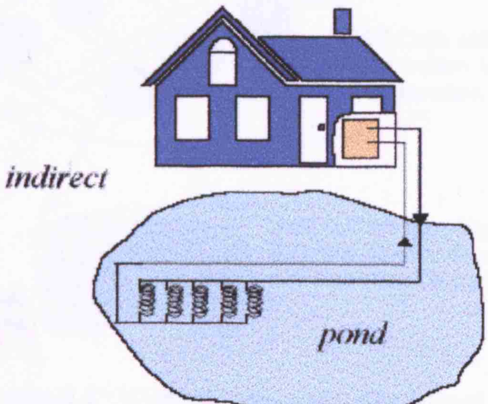


Figure 2.2: Closed- loop system
(Source: Geo-heat Center, Oregon Institute of Technology)

A water- antifreeze solution (or refrigerant in the case of a DX system), which has been chilled by the heat pump's refrigeration system to several degrees colder than the river's temperature, circulates through the piping, absorbing heat from the river. The recommended piping material is thermally fused HDPE tubing with ultraviolet (UV) radiation protection[1].

The medium (water or antifreeze solution) can flow through pipes anchored at the bottom of the river. Individual pipe coils are commonly used combined into a single circuit and attached to a frame. The piping networks of the closed-loop system resemble those used in ground-coupled heat pump systems. Both a large-diameter header between the heat pump and river coil and several parallel loops of piping in the river are required. The loops are spread out to limit thermal interference, hot spots, and cold pockets. While this layout is preferred in terms of performance, installation is more time consuming.

Many contractors simply unbind plastic pipe coils and submerged them in a loose bundle (figure 2.3). Some compensation for thermal interference is obtained by making the bundled coils longer than the spread coils. In the case of River Thames though where the water is continuingly flowing, thermal interference between the loops is nullified.

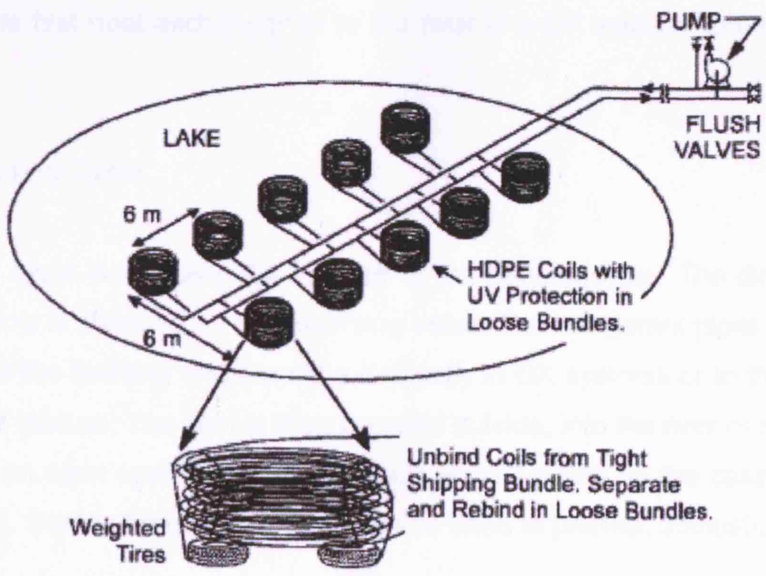


Figure 2.3[1]: Closed-loop coils' configuration

[1] Geothermal Energy: ASHRAE Applications Handbook (2003).

2.4 The Heating Cycle

In the heating cycle[1], the river's water, the antifreeze mixture, or refrigerant (which has circulated through the submerged piping system and picked up heat from the river), is brought back to the heat pump unit inside the building. It then passes through the refrigerant-filled primary heat exchanger for surface water or antifreeze mixture systems.

In DX systems the refrigerant enters the compressor directly, with no intermediate heat exchanger. The heat is transferred to the refrigerant, which boils to become a low-temperature vapour. In an open system, the surface water is then pumped back out and discharged into the river. In a closed-loop system, the antifreeze mixture or refrigerant is pumped back out to the submerged piping system to be heated again.

The reversing valve sends the refrigerant vapour to the compressor. The vapour is then compressed which reduces its volume, causing it to heat up. Finally, the reversing valve sends the now-hot gas to the condenser coil, where it gives up its heat. Air is blown across the coil, heated, and then forced through the ducting system to heat the building. Having given up its heat, the refrigerant passes through the expansion device, where its temperature and pressure are dropped further before it returns to the first heat exchanger or to the river in a DX system, to begin the cycle again.

2.5 The Cooling Cycle

The cooling cycle is basically the reverse of the heating cycle. The direction of the refrigerant flow is changed by the reversing valve. The refrigerant picks up heat from the air inside the building and transfers it directly in DX systems or to the river water or antifreeze mixture. The heat is then pumped outside, into the river or return well (in the case of an open system), or into the submerged piping (in the case of a closed-loop system). Some of this excess heat can be used to preheat domestic hot water.

[1] Heating and cooling with a heat pump: Natural Resources Canada/Energy Publications (2000).

3. THE USE OF THAMES AS A SOURCE-SINK FOR A SWHP SYSTEM

3.1 General Information on River Thames

River Thames, as presented in figure 3.1[1], is practically divided in two parts at Teddington Lock. The actions of the tides (the rise (flood) and fall (ebb) of the water level) is one of the most significant differences between the River Thames above and below Teddington.

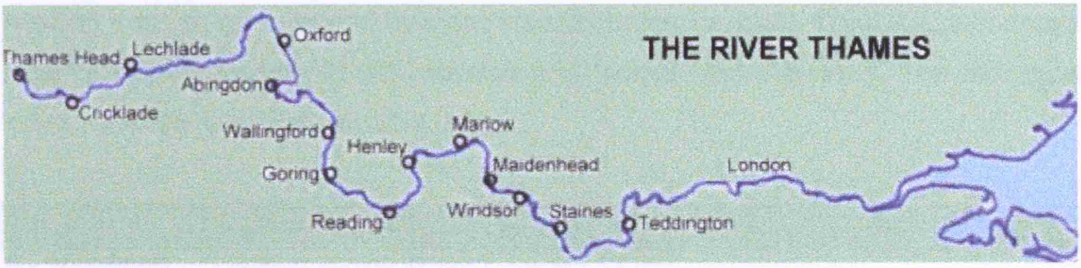


Figure 3.1: River Thames

The non-tidal Thames comes to an end when it reaches Teddington Lock. Passing through one of its three locks the River becomes tidal and it ultimately leads to the estuary and the North Sea. The difference in the height of water at high and low tide (the tidal range) depends upon whether or not they are Spring (largest range) or Neap (smallest range) tides. The difference in water level between Mean High Water and Mean Low Water (Mean Range) at London Bridge varies from 4.6 meters at Neap tides to 6.6 meters at Spring tides. The tidal River also varies in width along its length.

The other significant difference between water above and below Teddington is the amount of salt in the water (its salinity). Above Teddington the River contains fresh water whereas below Teddington the water is saline but the degree of salinity changes with the state of the tide and the volume of fresh water coming downstream. River Thames receives waste water discharge from a population of over 12 million people of whom 7 million live in the London conurbation.

3.2 Thames' Water Quality

The selection of the system that will be used (in terms of whether a closed or an open loop system will be used) is highly dependent on the quality of the water as it

[1] Source: www.riverthames.co.uk

will be discussed later. As previously mentioned, Thames' water in the London area is not fresh as it contains amounts of salt.

According to data collected by the UK Environment Agency, regarding the biology of the river, macro-invertebrates (small animals that can be seen with the naked eye) in the sample are compared with the range of species that would be expected to be found in the river if it was not polluted and assign a grade. Natural changes that happen such as geology and flow are also taken into account. The UK Environment Agency classifies water quality according to biology and chemistry. The biological classification is described in table 3.1:

Classification	Description
A - very good	Biology similar to that expected for an unpolluted river.
B - good	Biology is a little short of an unpolluted river.
C - fairly good	Biology worse than expected for unpolluted river.
D - fair	A range of pollution tolerant species present.
E - poor	Biology restricted to pollution tolerant species.
F - bad	Biology limited to a small number of species very tolerant of pollution.

Table 3.1: Biological Classification of the Thames

Samples are collected from 13 selected locations throughout the London area. Latest results indicate that Thames' biological classification is D on average.

The chemical classification of the river is described in table 3.2.

Classification	Likely uses and characteristics *
A - very good	All abstractions. Very good salmonid fisheries. Cyprinid fisheries. Natural ecosystems.
B - good	All abstractions. Very good salmonid fisheries. Cyprinid fisheries. Ecosystems at or close to natural.
C - fairly good	Potable supply after advanced treatment. Other abstractions. Good cyprinid fisheries. Natural ecosystems or those corresponding to good cyprinid fisheries.

D – fair	Potable supply after advanced treatment. Other abstractions. Fair cyprinid fisheries. Impacted ecosystems.
E - poor	Low grade abstraction for industry. Fish absent or sporadically present, vulnerable to pollution.** Impoverished ecosystems. **
F - bad	Very polluted rivers which may cause nuisance. Severely restricted ecosystems.

* Providing other standards are met.

** Where the grade is caused by discharges of organic pollution.

Table 3.2: Chemical Classification of the Thames

Samples are collected from 55 selected locations throughout the London area. Latest results indicate that Thames' chemistry classification is E on average.

3.3 Thames' Thermal Behaviour and the City of London

London is in general known for its rain however the weather is not actually rainy but mostly unstable and unreliable. October to January are the rainiest times of the year, but the temperature rarely goes under freezing, even in the winter. In summer, it can be sunny and temperatures are generally pleasant. Heating degree-hours for 18°C base temperature and cooling degree-hours for 20°C base temperature are shown in table 3.3.

Month	Heating degree-hours	Cooling degree-hours
January	9,077	0
February	9,462	0
March	7,041	0
April	6,815	10
May	4,757	2
June	2,067	317
July	701	1,197
August	1,325	227
September	3,212	0
October	5,614	0
November	5,108	0
December	8,013	0
Annually	63,192	1,753

Table 3.3: Heating-cooling degree-hours for 18°C and 20°C respectively

Table 3.4 presents daily average minimum and maximum air temperature and average relative humidity at 9 am and 3 pm during the year.

Month	Min Air Temp.	Max Air Temp.	RH% (9 am)	RH% (3 pm)
January	-1.3	10.1	93	82
February	-2.2	9.7	92	80
March	1.4	13.1	80	66
April	0.0	13.7	74	63
May	3.5	19.7	76	68
June	6.2	23.5	68	58
July	10.3	30.3	67	49
August	9.4	25.6	70	56
September	7.5	20.7	84	68
October	1.4	17.3	91	73
November	2.6	17.1	95	87
December	-1.1	13.7	95	88

Table 3.4: Daily average minimum and maximum air temperature & average relative humidity at 9 am and 3 pm

It can be seen that the temperature drops significantly below the critical temperature of 5°C, which would negatively influence the performance of an air source heat pump. Additionally, relative humidity is quite high when air temperature is low. The combination of low air temperature and high relative humidity in London would lead to accumulation of frost on the evaporator surface of an air-source heat pump unit at certain hours of the day. This, in turn, would lead to reduced heating capacity and performance of the heat pump system. Unlike air-source heat pumps, SWHP systems do not require a defrost cycle. Water temperature of the river is much more stable than external air temperatures, and the heat pump unit itself is located inside; therefore, frost problems do not arise.

Thermal behaviour of water bodies in general is a complicated issue which demands detailed monitoring. In order to evaluate Thames' response to the external air temperature, hourly measurements of the water's temperature against the air temperature are required. The UK's Environment Agency has been monitoring the water's temperature at certain locations every 15 minutes; however there are no available data of the air temperature at the time of the measurements.

The locations of the measurements along the Thames route through London are at Putney, Vauxhall, Charing Cross, London Bridge, Cherry Garden, Cadogan Pier, Wandsworth Bridge and Hammersmith Bridge. Data collected from the last six years (1999- 2004) reveal no significant differences in water temperatures between these locations. Additionally there was only a slight variation in the water temperature during the same day. This behaviour can be explained in terms of thermal inertia of the water.

Figure 3.2 below presents maximum, minimum and average air temperatures as well as water temperatures as they were monitored at London Bridge in 1999. The reason that 1999 was selected is because it was the most recent weather file available for the next chapter's simulations.

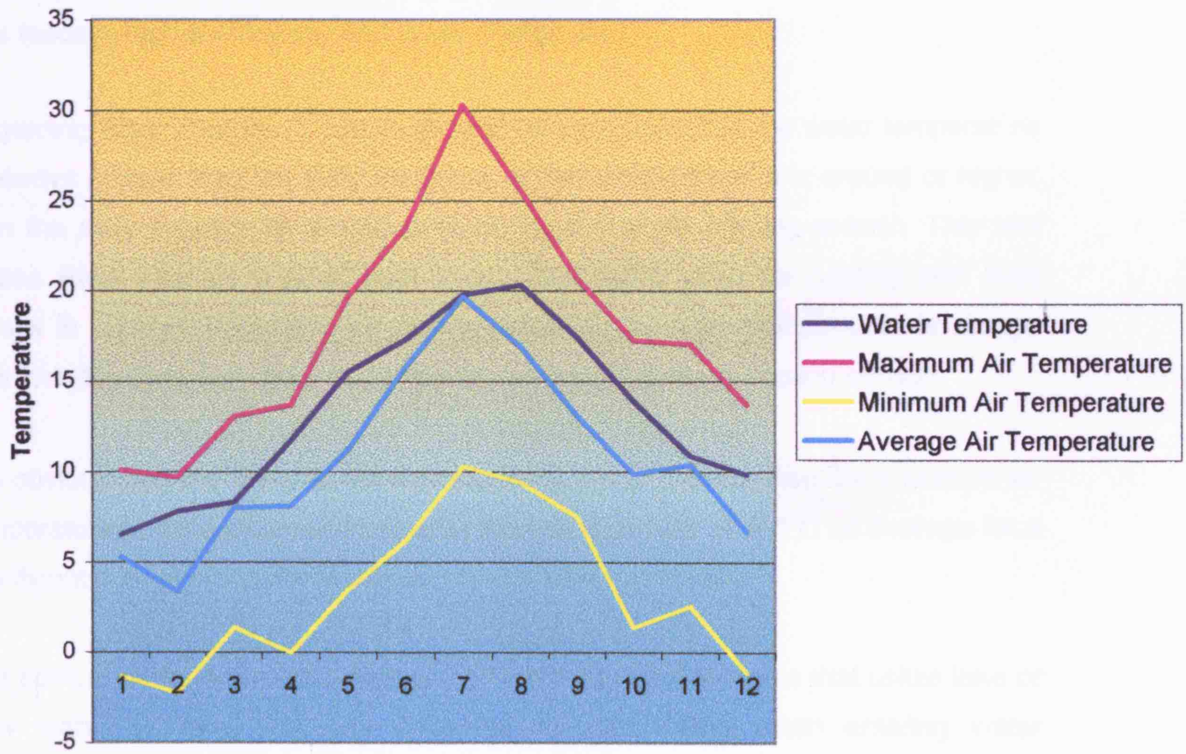


Figure 3.2: Maximum-minimum and average air and water temperatures

A temperature difference ranging from 11.4°C to 20.0 °C between the daily maximum and minimum air temperatures is evident from the figure. The River Thames temperature follows the daily average temperature pattern though it is in general a bit higher except in March, July and November when the temperatures are almost identical.

Perhaps the most important characteristic of heat pumps, particularly in the context of space heating/cooling, is that the efficiency of the unit and the energy required to operate it are directly related to the temperatures between which it operates. The difference between the temperature where the heat is absorbed (the "source") and the temperature where the heat is delivered (the "sink") is called the "lift"[1]. The larger the lift, the greater the power input required by the heat pump. This fact enhances the efficiency advantage of the geothermal heat pumps (SWHP in this case) over air-source heat pumps.

An air-source heat pump must remove heat from cold outside air in the winter and deliver heat to hot outside air in the summer. In contrast, the SWHP retrieves heat from relatively warm water in the winter and delivers heat to the same relatively cool water in the summer. As a result, SWHP systems, regardless of the season is always pumping the heat over a shorter temperature distance than the air-source heat pump. This leads to higher efficiency and lower energy use.

Regarding River Thames, It can in general be concluded that the water temperature is always greater than the daily minimum air temperature and it is around or higher than the daily average air temperature during the whole heating season. This fact makes River Thames a good heat source alternative to air for heating with heat pumps in London. Regarding its cooling potential, the water temperature is always less than the daily maximum air temperature during the whole cooling season.

It is obvious that, the water temperature is at least 5.0 °C lower than the maximum air temperature and the difference between the two is as high as 8.6°C on average for a significant portion of the cooling season (from May to August).

The cooling performance and capacity of the heat pump systems that utilize lake or river water as heat sink are accepted as outstanding when entering water temperature is between 13°C and 24°C[2]. Performance is good for the entering water temperatures below 29°C, and acceptable between 29°C and 35°C. If the water temperature is below 13°C, direct cooling should be considered although this is not possible in the case of River Thames during the typical cooling period as water's temperature from May to September is not lower than 15.5°C.

[1] An information survival kit for the prospective geothermal heat pump owner: Kevin Rafferty, P.E., U.S. Department of Energy/2001.

[2] Lakewater applications of water to air heat pumps: Kavanaugh SP, ASHRAE, 1990.

3.4 Water Resources Regulations

Another important factor that should be taken into account in order to implement this kind of technology is the legislation behind the use of water resources. Current legislation can prohibit a specific technology and this should be considered when selecting a system as will be analysed in the following chapter. According to the UK's Environment Agency which is responsible for the River Thames water usage, any development should primarily compose an Environmental Impact Assessment (EIA) before being allowed to proceed.

EC Directive (85/337/EEC) regarding the assessment of the effects of certain public and private projects on the environment was adopted in 1985 and subsequently amended by Directive (97/11/EC) to include certain water management projects. The amended directive has been given legal effect through the Water Resources (Environmental Impact Assessment) (England and Wales) Regulations 2003 SI No. 164 which came into force on 1st April 2003.

The effect of the Regulations is to require EIA to be carried out for water management projects that are relevant. A project is a relevant project if:

- It is a water management project for agriculture, including an irrigation project.
- In the case of a project involving water abstraction, the amounts abstracted exceed 20 cubic metres in any period of 24 hours.
- It would be likely to have significant effects on the environment by virtue inter alia of its nature, size or location.

It is obvious according to the above that a Surface Water Heat Pump system (SWHP) is a relevant project. Open and closed loop systems involve cases number 2 and 3 respectively.

Information regarding the characteristics of the project should be reported in detail, especially regarding the following:

1. The size of the project.
2. The cumulation with other projects (co-existence with other projects).
3. The use of natural resources.
4. The production of waste.
5. The risk of accidents, having regard in particular to substances or technologies used.

The environmental sensitivity of geographical areas likely to be affected by the project must also be considered, having regard, in particular, to the following:

1. The existing land use.
2. The relative abundance, quality and regenerative capacity of natural resources in the area.
3. The absorption capacity of the natural environment, paying particular attention to areas such as wetlands, densely populated areas and areas in which the environmental quality standards laid down in Community legislation have already been exceeded.

The potential significant effects of projects must be considered having regard in particular to the extent of the impact (geographical area and size of the affected population), the transfrontier nature of the impact, the magnitude and complexity of the impact, the probability, duration, frequency and reversibility of the impact.

Other information regarding the project required by the EIA is an outline of the alternatives studied by the developer and an indication of the reasons for his choice, taking into account the environmental effects. Additionally a description of the measures envisaged to prevent, reduce and where possible offset any significant adverse effects on the environment must also be included.

3.5 Selection of SWHP System's Loop Type Based on Thames' Characteristics

The final selection of the system that can potentially be used in the case of the Thames, in terms of whether it is an open or a closed-loop system, must take into consideration efficiency advantages as well as environmental restrictions.

The use of surface water as a cooling or heating water through an open-loop system has the following disadvantages:

- It can have several environmental consequences: water animals in the surface water can be damaged when they are sucked into the cooling system; when the heated cooling water is released to the surface water, the temperature of the water increases and lethal effects can occur for the most sensitive species.

- General problems regarding the disposal of the water after once-through the heat pump as separate disposal wells can be costly.

- Open-loop systems have more problems than either conventional systems or closed-loop geothermal systems because they bring outside water into the unit. This can lead to clogging, mineral deposits, and corrosion in the system. River Thames has amounts of salt in London area and the quality of water is not high as analysed in Section 3.2. Contractors often suggest cupronickel heat exchangers which are effective for salt water applications though for the other commonly encountered water quality issues as those of River Thames (excessive particles, pollutants, organic matters etc) cupronickel construction is of little if any value.

- Local and state regulations taking into account the Water Resources Regulations that were analysed in the previous chapter will probably not approve such a technology especially if it involves an extended scheme concerning a large number of buildings along the river's banks.

- Water temperature should be typically over 5.5 °C to avoid freezing of the heat exchanger.

On the other hand, the closed-loop lake water heat pump system has several advantages over the open-loop system. One advantage is the reduced fouling resulting from the circulation of clean water (or water-antifreeze solution) through the heat pump. A second advantage is the reduced pumping power requirement. This results from the absence of an elevation head from the lake surface to the heat pumps. A third advantage of a closed-loop is that it is the only type recommended if a river temperature below 5.0 °C is possible.

A closed-loop system though has the disadvantage of a lower performance of the heat pump because the circulation fluid temperature drops slightly below the river temperature.

Taking all of the above into consideration, the most favourable system in the case of River Thames appears to be a closed- loop surface water heat pump system. Nevertheless, both systems will be examined in the following chapter in order to evaluate the differences in their efficiency in terms of energy consumption.

4. METHODOLOGY

4.1 Introduction

The aim of this chapter is to evaluate the performance of a SWHP system, in terms of its energy consumption and its CO_2 emissions, with the use of a simulation software (E-QUEST: Quick Energy Simulation Software) which will be described in the following section, compared to both a conventional variable air volume (VAV) air-conditioning with air-cooled water chillers and gas boiler heating system as well as to a WLHP system which includes a cooling tower and a gas boiler.

The process that will be followed can be described as below:

- Design of a base model that will be used in E-QUEST simulations and calculation of its energy demands.
- Simulation of the model using conventional variable air volume (VAV) air-conditioning with air-cooled water chillers and a gas boiler heating system.
- Simulation of the model using a WLHP system which includes a cooling tower and a gas boiler.
- Simulation of the model using a WLHP system combined with an open-loop SWHP system.
- Simulation of the model using a WLHP system combined with a closed-loop SWHP system.

4.2 Software Description

E-QUEST is a free- download simulation software which is supported as a part of the Energy Design Resources program which is funded by California (U.S.) utility customers and administered by Pacific Gas and Electric Company, San Diego Gas & Electric, and Southern California Edison, under the auspices of the California Public Utilities Commission.

This simulation tool is designed to perform detailed analysis of building design technologies using building energy use simulation techniques in order to calculate hour-by-hour energy consumption over an entire year (8,760 hours) using hourly weather data for the location under consideration. This is accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module with an enhanced DOE-2-derived building energy use simulation program.

The process of creating the building energy model involves following a series of steps that involve describing the features of the design that would impact energy use, such as:

- Architectural design.
- HVAC equipment.
- Building type and size.
- Floor plan layout.
- Construction materials.
- Area usage and occupancy.
- Lighting system.

4.3 Model Description

4.3.1 Description of the Building

The building that will be used in the simulations is a typical mid-rise office building. The procedure involving the definition of the building's characteristics is described below:

- Weather: The first step prior to the development of the building is to select the appropriate weather file. E-QUEST uses specially formatted binary "packed" weather type files. The weather file that will be used in the simulations is a London- Kew 1999 weather file and for this reason River Thames' temperature data recorded the same year (1999) will be used.
- The building's dimensions: The building has a total floor area of 9,000 sq.m and has 6 floors (1,500 sq.m each). It has a rectangle footprint shape (50.00 x 30.00 m) elongated along the east-west axis. The floor to ceiling height is 2.7 m.
- Zoning: The next important step is to "zone" the internal spaces of the building. A "zone" implies an area or collection of spaces within a building having similar patterns and schedule of heat losses/gains and usage. For this purpose the building was zoned into three categories (first floor, mid floors and top floor) in combination with a perimeter-vs-core pattern with a perimeter zone depth of 6[1] m.
- Building Elements: The building has a metal frame and all its elements were selected in order to comply with the Building Regulations (within the minimum U-Values limitations) though not super- insulated as the purpose of this study is to

[1] CIBSE Building Energy Code 2: Energy Demands for Air-Conditioned Buildings (1999).

examine the performance of the particular HVAC system in a conventional building. All windows have double low-e coated glazing with internal blinds while the estimated floor to floor window area of the building is 55.4%. This is a relatively high percentage which reflects the general tendency of commercial buildings to use increased amounts of glazing surfaces.

- Tightness- Infiltration: The construction of the base model is considered to be tight as a typical new construction thus all joints and seams between windows, walls, doors, etc. have been well sealed to prevent air leakage. Infiltration rate in the perimeter zones is considered to be 0.5 ACH while infiltration rate in the core zones is considered to be 0.2 ACH.
- Allocation of Activity Areas: In order to estimate internal conditions of each space, allocation of each activity areas must be performed so as to take into account the associated occupant densities and the design outdoor air ventilation rates. Activity areas in this case were allocated as described in table 4.1.

	Area Type	Percent Area (%)	Design Max Occup (sf/person)	Design Ventilation (CFM/per)	Assign First To: 1st Flr	Core	Perim
1:	Office (Open Plan)	40.0	150.0	20.00	☐	☐	☑
2:	Office (Executive/Private)	30.0	225.0	20.00	☐	☐	☑
3:	Corridor	10.0	150.0	7.50	☐	☑	☐
4:	Lobby (Office Reception/Waiting)	5.0	150.0	15.00	☑	☐	☑
5:	Restrooms	5.0	52.5	50.00	☐	☑	☐
6:	Conference Room	4.0	22.5	20.00	☐	☐	☑
7:	Mechanical/Electrical Room	4.0	450.0	22.50	☑	☑	☐
8:	Copy Room (photocopying equipment)	2.0	187.5	93.75	☐	☑	☐
	Percent Area Sum:	100.0					

Table 4.1: Allocation of Activities Areas

For each Activity Area, there are inputs for type, percent of total floor area, occupant density as well as checkboxes to indicate if the activity area should be assigned to the first floor, core zones, perimeter zones or any other combination. The building is mechanically ventilated according to the design ventilation rates that are presented in the table.

It should be noted at this point that minimum design airflow will be used in order to set a minimum on the design airflow supplied to each space. Minimum design airflow regards airflow at design (maximum) conditions and must not be confused with VAV minimum airflow. Minimum design airflow can have a significant impact on fan energy use if it is set too high. It is in general common practice to provide at least 6 ACH[1] to each space to ensure adequate ventilation and air movement for comfort.

- Internal Loads- Schedules: The building's operation schedule is that of a typical office building thus it will operate daily on weekdays from 9:00 to 18:00. Internal loads per activity area are described in table 4.2.

Area Type	Percent Area (%)	Lighting (W/SqFt)	Task Lt (W/SqFt)	Plug Lds (W/SqFt)	Schedule Main	Schedule Alt
1: Office (Open Plan)	40.0	1.30	0.40	1.50	●	○
2: Office (Executive/Private)	30.0	1.30	0.00	1.50	●	○
3: Corridor	10.0	0.60	0.00	0.20	●	○
4: Lobby (Office Reception/Waiting)	5.0	1.10	0.00	0.50	●	○
5: Restrooms	5.0	0.60	0.00	0.20	●	○
6: Conference Room	4.0	1.60	0.00	1.00	●	○
7: Mechanical/Electrical Room	4.0	0.70	0.00	0.20	●	○
8: Copy Room (photocopying equipment)	2.0	1.50	0.00	3.00	●	○

Table 4.2: Internal Loads

- Thermostat Temperatures: The Thermostat Cooling Setpoint, used to indicate the occupied thermostat setpoint for cooling in all zones is set to 25°C while the Thermostat Heating Setpoint is set to 21°C. Cooling- Heating Indoor and Supply Design Temperatures must also be defined in order to size airflow. In this case Cooling and Heating Indoor Design Temperatures are set to 24°C and 22°C respectively. Cooling and Heating Supply Design Temperatures are set to 16°C and 32°C respectively.

[1] CIBSE Guide B2: Ventilation and Air- Conditioning (2001).

4.3.2 Thermal Performance of the Building

Taking all of the above into account (construction materials, internal loads, schedules etc) the building's heating and cooling loads were calculated. As it was predicted even during the winter there are significant cooling loads particularly in the activity areas which are located in the core of the building. This is due to the high internal loads of office buildings in combination with their operating schedules.

Maximum cooling load occurred in mid August at noon time where there was a demand for 591 kWh/hr while maximum heating load occurred in late December early in the morning where there was a demand for 138 kWh/hr.

Figure 4.1 presents a monthly summary of the building's cooling and heating demands. As it is obvious there are occasions where there is a simultaneous need for cooling and heating depending on the type of the activity area as well as on its location.

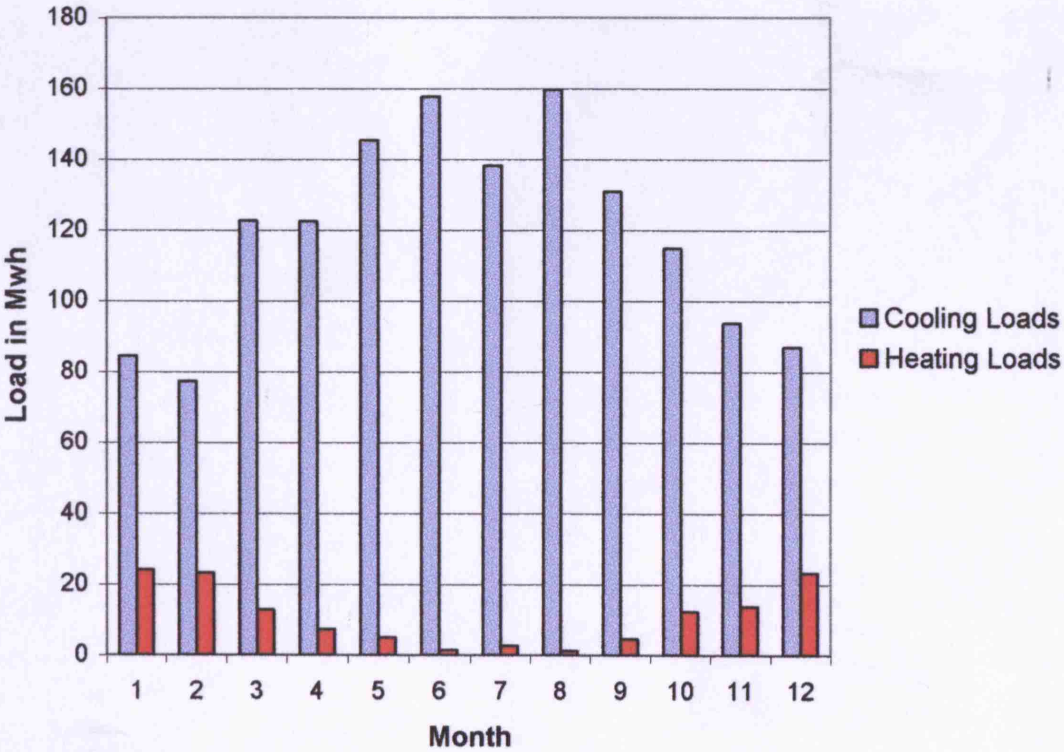


Figure 4.1: Monthly Heating and Cooling Demands

4.3.3 Description of the Building's HVAC Equipment

As mentioned in this chapter's introduction section four different types of HVAC equipment will be examined. These systems, as they were simulated in EQUEST, are described in the following sections.

4.3.3.1 VAV Air- conditioning with Air-cooled Water Chillers and a Gas Boiler

This is a central HVAC system which is commonly used in office buildings and uses chilled water as a cooling medium. In this case air- cooled water chillers are being used for cooling while heating is generated by a gas boiler and distributed through a hot water piping.

The system therefore has three major subsystems: the air-handling unit, the chilled water plant and the boiler plant. The air-handling units supply air to the conditioned spaces. Air is taken by the units either from outside or from the space itself through a return air system.

When the enthalpy of outdoor air is lower than that of the return air, it is more economical to use the outdoor air for cooling of the building than to circulate return air. When the outdoor air is warmer than return air, or when the outdoor temperature is very low, a minimum amount of outdoor air will be mixed with the return air in order to provide fresh air ventilation for removal of indoor contaminants such as carbon dioxide. The air is filtered and conditioned to the desired temperature (the air may require preheating rather than cooling, depending on outdoor conditions).

The chiller is essentially a packaged vapour compression cooling system which provides cooling to the chilled water and rejects heat to the condenser water. The condenser water pump circulates the condenser water through the chiller's condenser, to the cooling tower, and back. The cooling tower rejects heat to the environment through direct contact of the condenser water and the cooling air. The chilled water system supplies chilled water for the cooling needs of all the building's air-handling units.

The heating water system includes a gas condensing boiler and a pump for circulating the heating water. The boiler's efficiency thus its design combustion efficiency at design load is set to 90 %.The heating water in this case will serve preheat coils in air-handling units.

The most important characteristic of this HVAC system is that the air flow to the conditioned space is controlled. Variable Air Volume (VAV) systems meet changing load requirements by adjusting the amount, rather than the temperature, of cool air that flows to each zone, As a zone's cooling load decreases, a damper in its VAV control box starts to close, reducing the supply of cool air. As a result of the reduced airflow there are significant savings in the consumed fan energy.

4.3.3.2 WLHP System Including a Cooling Tower and a Gas Boiler

This system (figure 4.2), as was described in Chapter 1, is a heating and cooling system that places heat pumps in each building zone while the heat pumps are connected with a re-circulating two-pipe distribution system. The heat pumps in this particular system will be packaged units in single cabinets that include the compressor, the heat exchangers, the fan, the filter and the controls. These units will be hung above the ceiling.

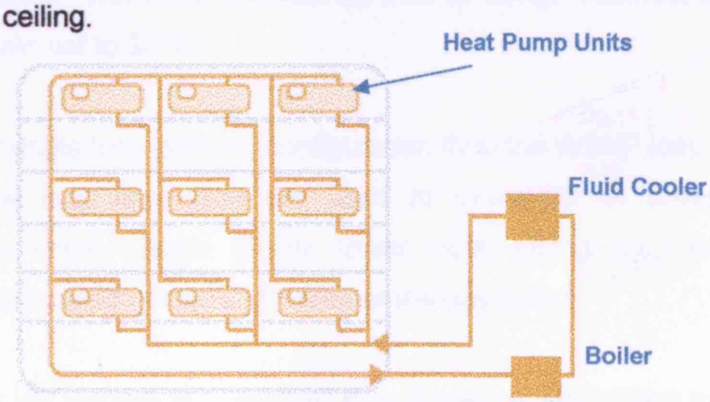


Figure 4.2: WLHP System Including Fluid Cooler and Boiler

Heat pumps operating in cooling mode will extract heat from the room and deposit it into the water circuit. Other heat pumps which are in heating mode will take heat from the circuit. In this way the rejected heat, for example from computer rooms, can be recovered and deposited into rooms demanding heating.

The temperature of the loop will be maintained between 16°C and 32°C. A fluid cooler will remove heat from the loop temperature when it exceeds 32°C and heat will be added with a gas boiler if the temperature falls below 16°C.

The fluid cooler isolates the WLHP system's water from the air flow via a heat exchanger incorporated within the cooler itself. A fan blows air through one side of the heat exchanger while a spray pump simultaneously sprays water into the air. The WLHP system's fluid circulates through the other side of the heat exchanger. The spray pump is integral to the unit, and consumes a constant amount of power whenever the fluid cooler is operating. The temperature of the water in the loop is controlled as a variable speed fan will modulate the airflow so that the rejection capacity exactly matches the load at the desired setpoint.

The reason that a fluid cooler was preferred instead of an open tower (cooling tower that directly exposes the fluid in the condenser loop to the air flowing through the tower) is that open towers are not normally used with devices such as water loop heat pumps since oxygen and other contaminants may be introduced into the loop from the tower.

Regarding the heating configuration a gas condensing boiler is used, same as the previous system's boiler. The boiler's efficiency thus its design combustion efficiency at design load is again set to 90 %.

This system has a "single loop pumps" configuration thus the WSHP loop pumps are located only at the loop level and are used to overcome all pressure drops associated with the entire system (boiler, tower, coils, piping, etc.) therefore no individual pumps are located at the fluid cooler or the gas boiler.

The flow in the WLHP system is "variable" thus it can be modulated to meet load requirements. This function demands two-way valves throughout the system. Since the flow in the WLHP system is variable, a loop pump control system has to be defined in order to indicate how the loop pump modulates as the flow varies. In this case a "VSD" (Variable Frequency Drive) control system will be used.

The method of operation control for the water-source heat pump system is "on demand" therefore the WLHP system will not be activated activate until there is actually a cooling or heating load. This operation mode, which is the most energy-efficient, causes the loop to be active only when a coil load (thus a demand of a thermostat) occurs.

4.3.3.3 WLHP System Combined with an Open-loop SWHP System

In this system (figure 4.3) the Thames is used as a heat source and as a "sink" instead of the fluid cooler and the gas boiler that were described previously. Since an open-loop configuration is being used, the temperature of the river loop's fluid is equal to the river's temperature. In order to incorporate the Thames varying water temperatures throughout the year an annual schedule of the river's temperature was developed. The flow in the WLHP system is again "variable" as in the previous system.

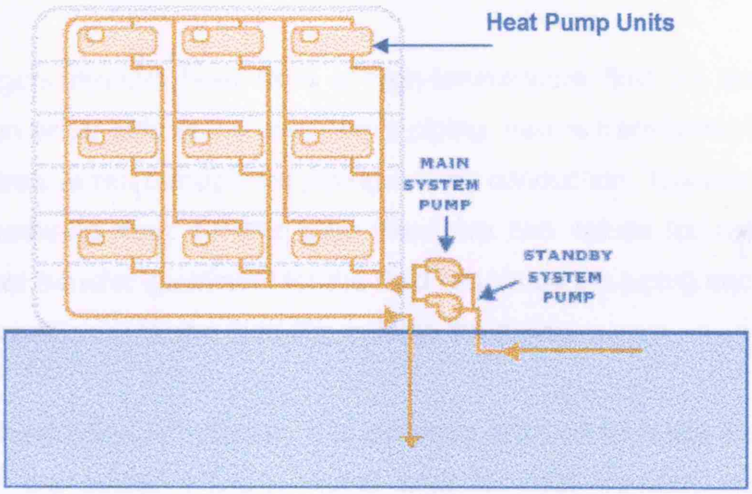


Figure 4.3: WLHP System Combined with an Open-loop SWHP System

4.3.3.4 WLHP System Combined with a Closed-loop SWHP System

Since E-QUEST is not yet capable of modelling a closed-loop SWHP system (figure 4.4), its performance will be estimated based on general principles of thermodynamics. The open-loop SWHP system, when compared to a closed- loop, provides higher operating efficiencies. This is due to the resistance of the pipe to heat transfer. Heat exchange in this case is conducted through the heat exchangers, which are devices that are used to transfer thermal energy from one fluid to another without mixing the two fluids.

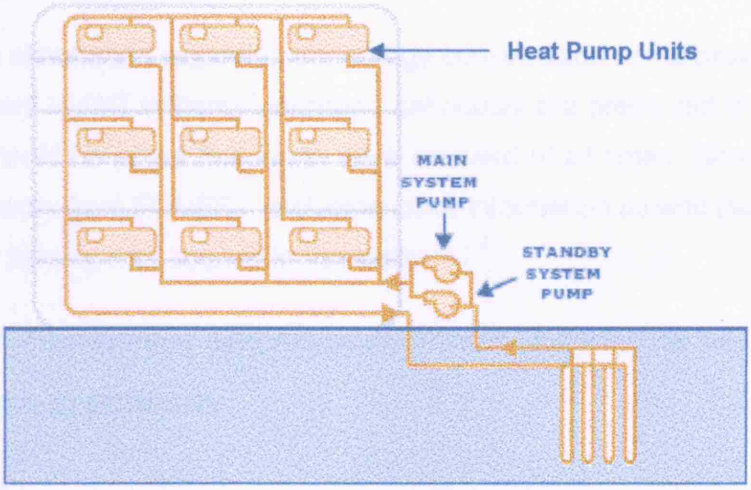


Figure 4.4: WLHP System Combined with a Closed-loop SWHP System

Heat exchangers remove heat from a high-temperature fluid by convection and conduction. On either side of the river loop's piping, heat is transferred by convection while heat is transferred through the piping wall by conduction. Therefore in this case there is a combined heat transfer thus there are two values for heat transfer, a convective heat transfer coefficient for the fluid film inside the piping and a convective heat transfer coefficient for the fluid film outside the piping.

In combined heat transfer patterns, it is common practice to relate the total rate of heat transfer, the overall cross-sectional area for heat transfer, and the overall temperature difference using the overall heat transfer coefficient. The overall heat transfer coefficient combines the heat transfer coefficient of the two heat exchanger fluids (the river's water and the water or antifreeze solution which runs inside the loop) and the thermal conductivity of the heat exchanger tubes.

According to ASHRAE[1] the circulation fluid temperature in a closed-loop system differs from 2°C to 7°C (below or above depending on the heat flow) from the river's temperature. Taking this into account simulation of the SWHP system will be performed with the adjusted temperatures.

[1] ASHRAE: HVAC Applications, SI Edition (2003).

4.4 Simulation Results

Results of the simulations regarding the energy consumption of the base model using the four different HVAC systems described previously are presented in the following sections. It should be noted that loads were satisfied at all times. Simulation results as derived directly from EQUEST, including other information as well (such as energy consumed for lighting etc.) appear in Appendix A.

4.4.1 VAV Air- conditioning with Air-cooled Water Chillers- Gas Boiler Results

MONTHLY DATA: ELECTRICITY

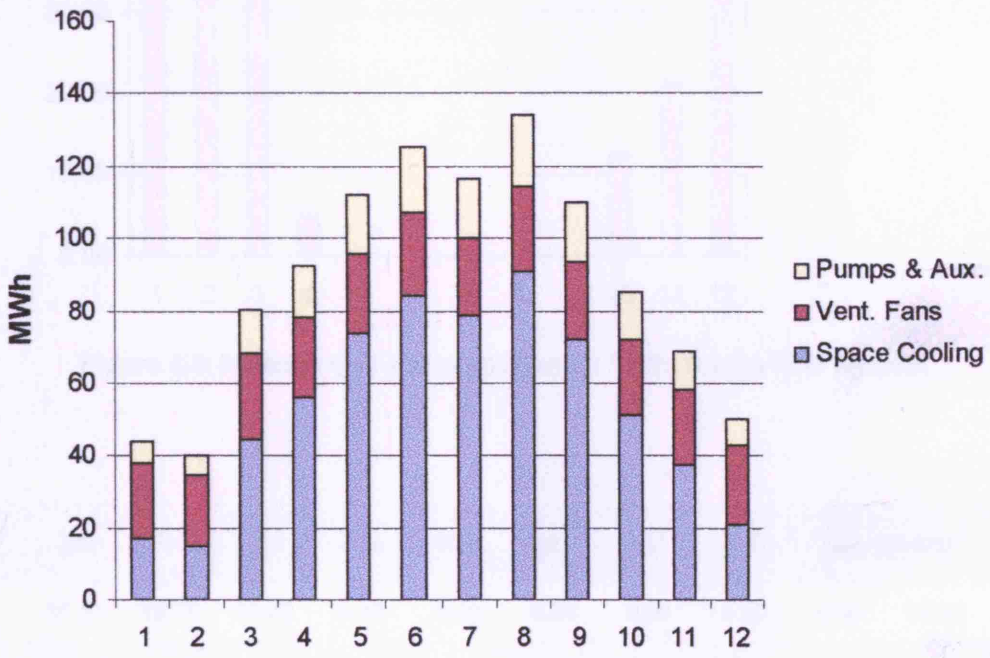


Figure 4.5: Monthly Electric Consumption (in MWh) for the VAV System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space Cooling	17.3	14.7	44.4	56.2	73.7	84.2	78.9	90.5	71.8	51.4	37.2	21.1
Heat Rejection	-	-	-	-	-	-	-	-	-	-	-	-
Space Heating	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	20.9	19.8	24.0	21.9	22.0	23.0	20.9	24.0	21.9	20.9	20.9	21.9
Pumps & Aux.	5.8	5.5	11.9	14.2	16.6	18.3	16.8	19.4	16.2	13.0	10.6	6.8
TOTAL	44	40	80.3	92.3	112.3	125.5	116.6	133.9	109.9	85.3	68.7	49.8

Table 4.3: Monthly Electric Consumption (in MWh) for the VAV System

MONTHLY DATA: GAS

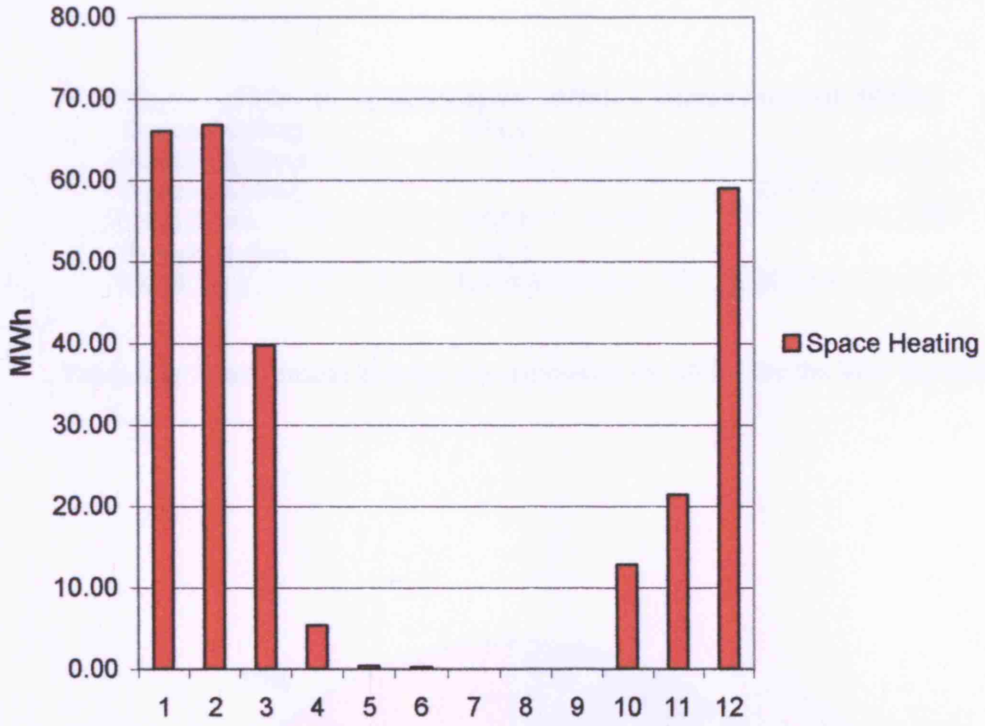


Figure 4.6: Monthly Gas Consumption (in MWh) for the VAV System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space Heating	66.03	66.79	39.69	5.39	0.40	0.26	0.00	0.00	0.00	12.82	21.36	58.97
TOTAL	66.03	66.79	39.69	5.39	0.40	0.26	0.00	0.00	0.00	12.82	21.36	58.97

Table 4.4: Monthly Gas Consumption (in MWh) for the VAV System

ANNUAL DATA:

	Electricity (in MWh)	Natural Gas (in MWh)
Space Cooling	641.6	-
Heat Rejection	-	-
Space Heating	-	271.73
Vent. Fans	262.2	-
Pumps & Aux.	155.1	-
Total	1,058.9	271.73

Table 4.5: Total Annual Energy Consumption (in MWh) for the VAV System

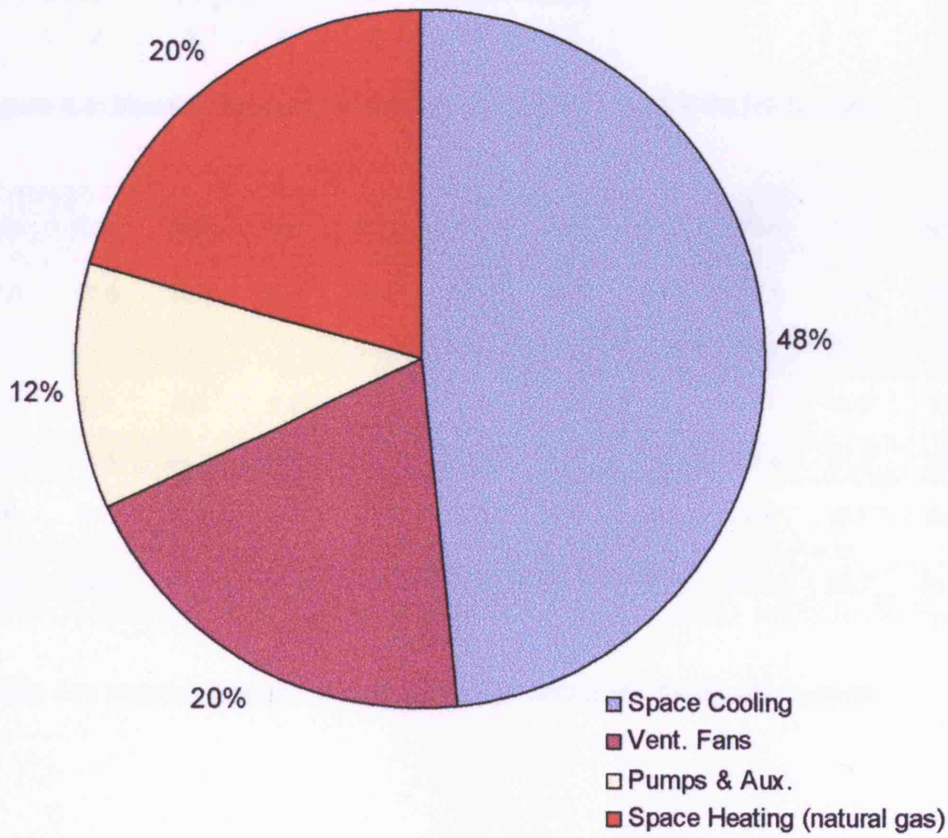


Figure 4.7: Total Annual Energy Consumption (in MWh) for the VAV System

4.4.2 WLHP System Including a Cooling Tower and a Gas Boiler Results

MONTHLY DATA: ELECTRICITY

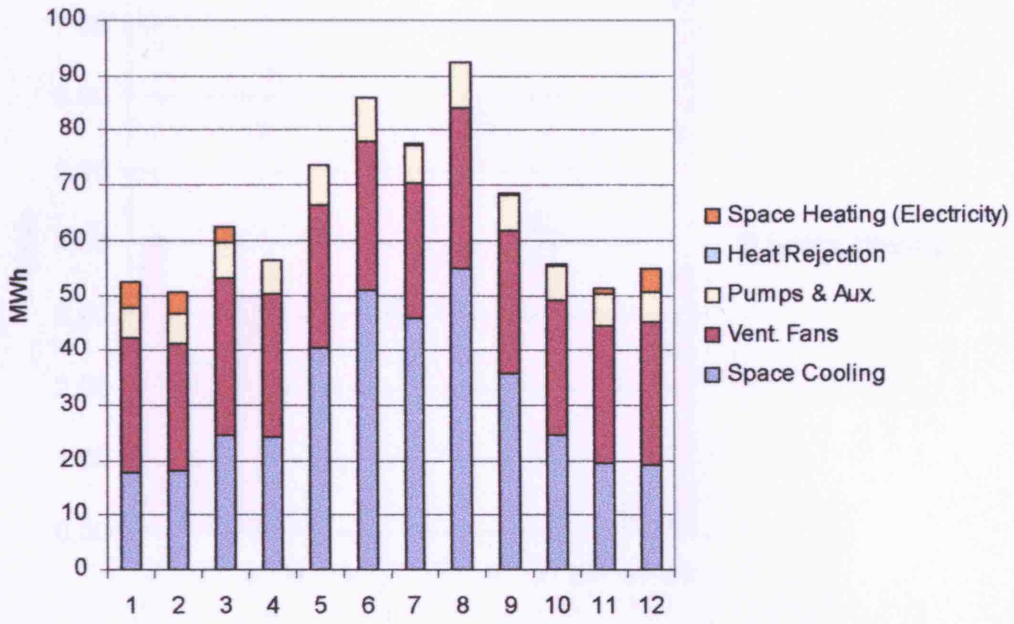


Figure 4.8: Monthly Electric Consumption (in MWh) for the WLHP System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space Cooling	17.6	17.9	24.6	24.2	40.6	51.0	45.7	54.7	35.8	24.5	19.6	19.2
Heat Rejection	-	-	-	-	0.05	0.1	0.1	0.1	0.05	-	-	-
Space Heating	4.8	4.0	3.0	0.1	-	-	-	-	-	0.4	1.2	4.3
Vent. Fans	24.7	23.4	28.4	25.9	26.0	27.1	24.7	28.4	25.8	24.7	24.7	25.9
Pumps & Aux.	5.4	5.2	6.4	6.2	7.1	7.7	7.0	8.2	6.8	6.1	5.8	5.3
TOTAL	52.5	50.5	62.4	56.4	73.75	85.9	77.5	91.4	68.45	55.7	51.3	54.7

Table 4.6: Monthly Electric Consumption (in MWh) for the WLHP System

MONTHLY DATA: GAS

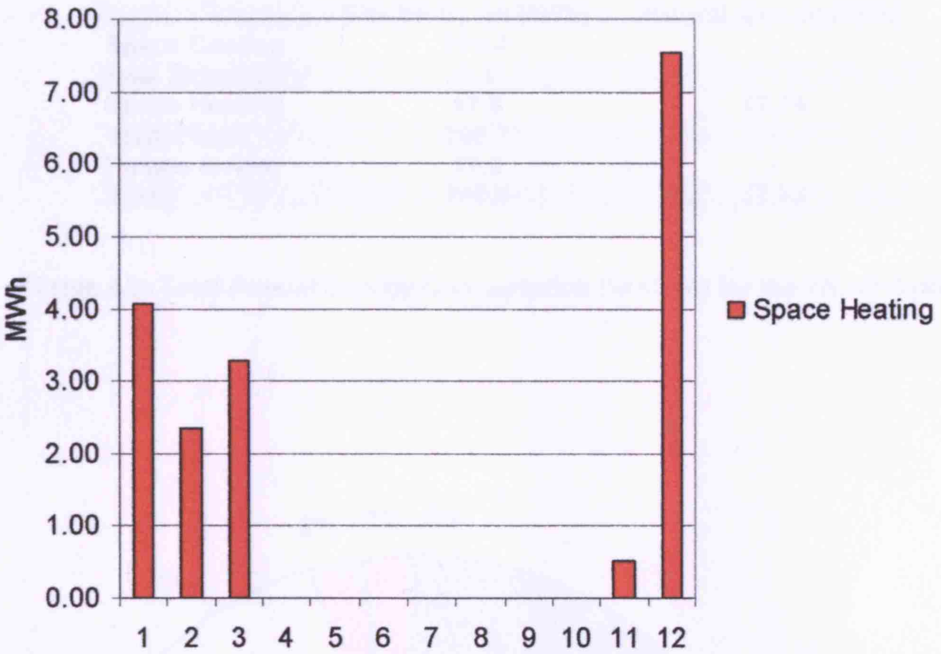


Figure 4.9: Monthly Gas Consumption (in MWh) for the WLHP System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space Heating	4.08	2.34	3.28	-	-	-	-	-	-	-	0.51	7.53
TOTAL	4.08	2.34	3.28	-	-	-	-	-	-	-	0.51	7.53

Table 4.7: Monthly Gas Consumption (in MWh) for the WLHP System

ANNUAL DATA:

	Electricity (in MWh)	Natural Gas (in MWh)
Space Cooling	375.4	-
Heat Rejection	0.4	-
Space Heating	17.8	17.74
Vent. Fans	309.7	-
Pumps & Aux.	77.2	-
Total	780.5	17.74

Table 4.8: Total Annual Energy Consumption (in MWh) for the WLHP System

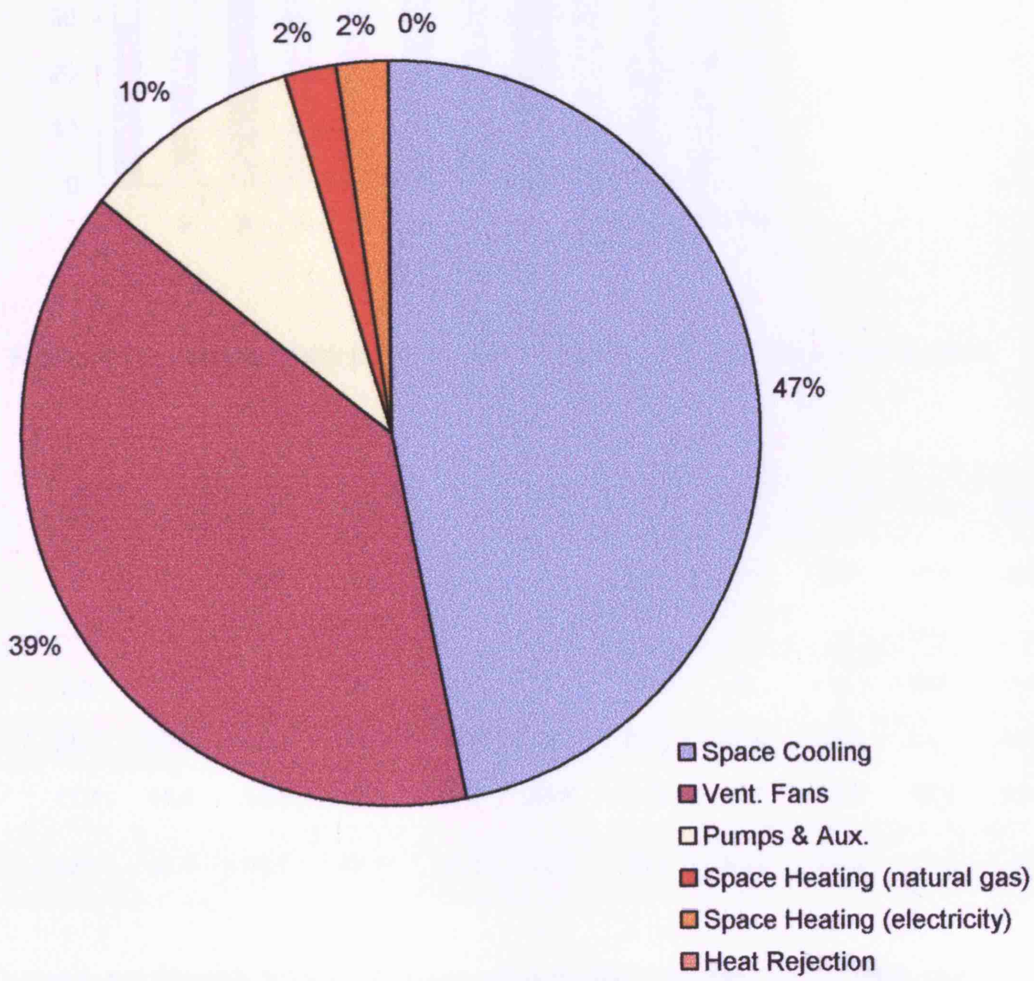


Figure 4.10: Total Annual Energy Consumption (in MWh) for the WLHP System

4.4.3 WLHP System Combined with an Open-loop SWHP System Results

MONTHLY DATA: ELECTRICITY

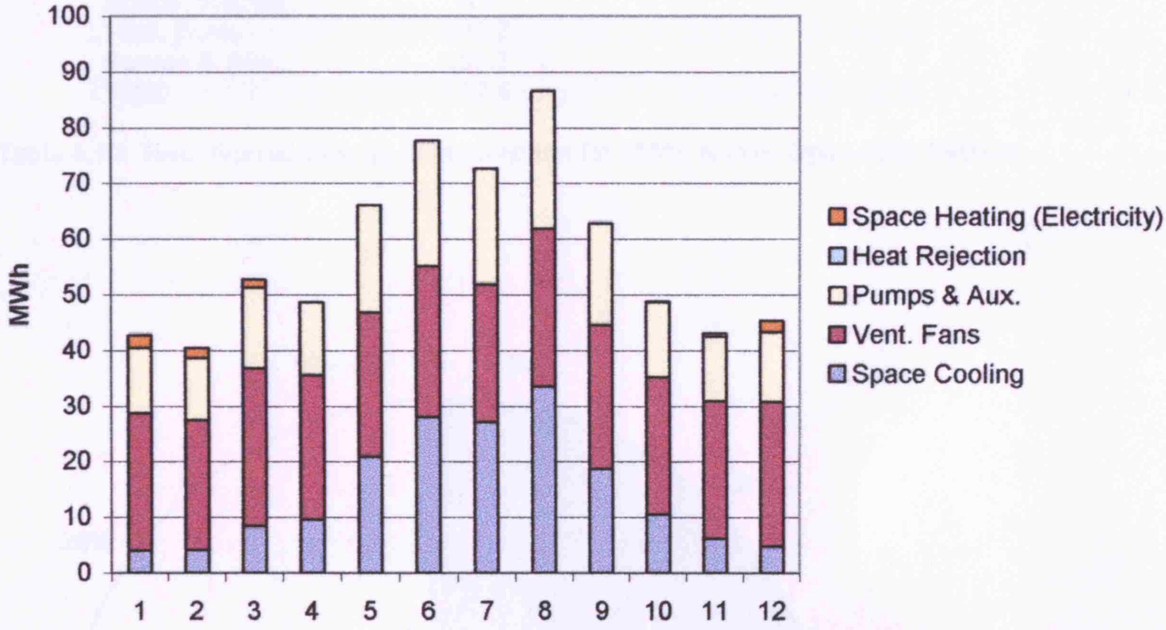


Figure 4.11: Monthly Electric Consumption (in MWh) for the Open-loop System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space Cooling	4	4.1	8.4	9.6	20.8	28	27.1	33.5	18.7	10.5	6.2	4.8
Heat Rejection	-	-	-	-	-	-	-	-	-	-	-	-
Space Heating	2.3	1.8	1.5	0	0	0	0	0	0	0.2	0.5	2
Vent. Fans	24.7	23.4	28.4	25.9	26	27.1	24.7	28.4	25.8	24.7	24.7	25.9
Pumps & Aux.	11.7	11.1	14.4	13.1	19.3	22.6	20.9	24.7	18.3	13.4	11.6	12.6
TOTAL	42.7	40.4	52.7	48.6	66.1	77.7	72.7	86.6	62.8	48.8	43	45.3

Table 4.9: Monthly Electric Consumption (in MWh) for the Open-loop System

ANNUAL DATA:

	Electricity (in MWh)	Natural Gas (in MWh)
Space Cooling	175.7	-
Heat Rejection	-	-
Space Heating	8.3	-
Vent. Fans	309.7	-
Pumps & Aux.	193.7	-
Total	687.4	-

Table 4.10: Total Annual Energy Consumption (in MWh) for the Open-loop System

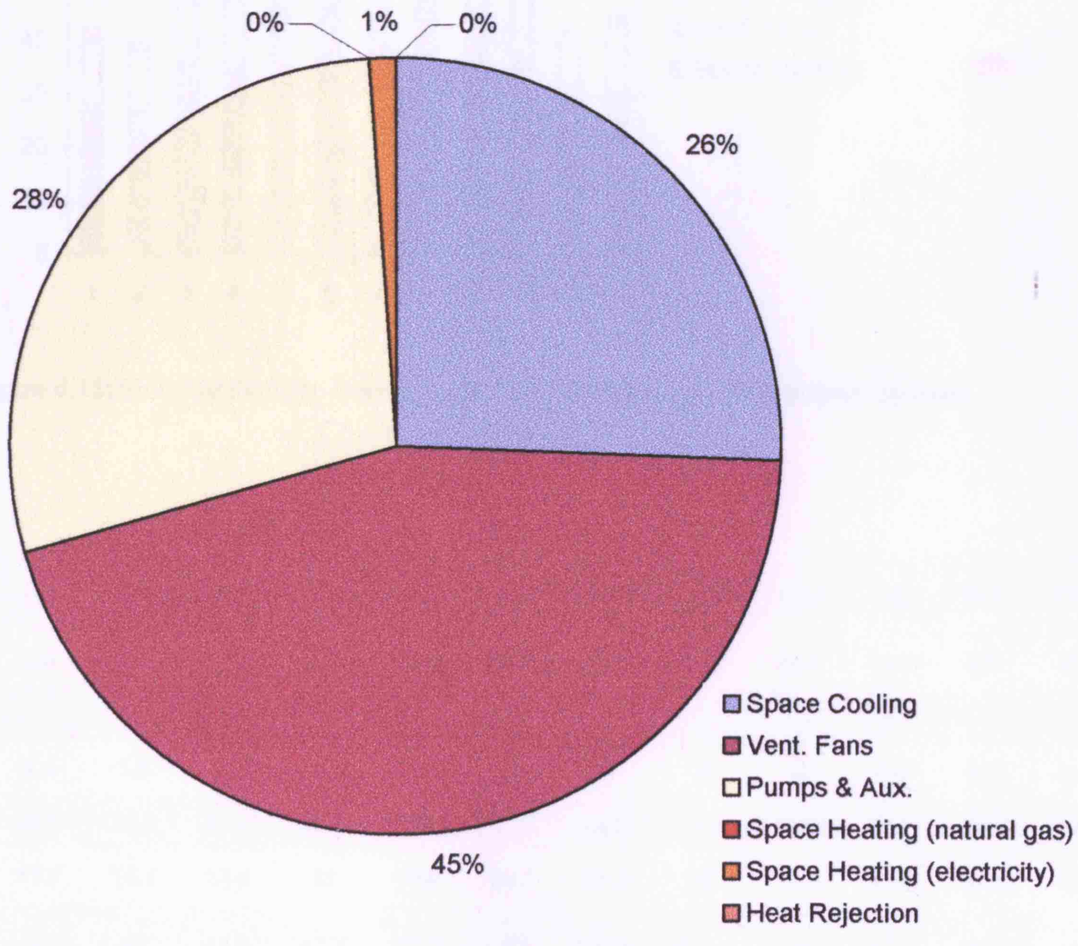


Figure 4.12: Total Annual Energy Consumption (in MWh) for the Open-loop System

4.4.4 WLHP System Combined with a Closed-loop SWHP System Results

MONTHLY DATA: ELECTRICITY

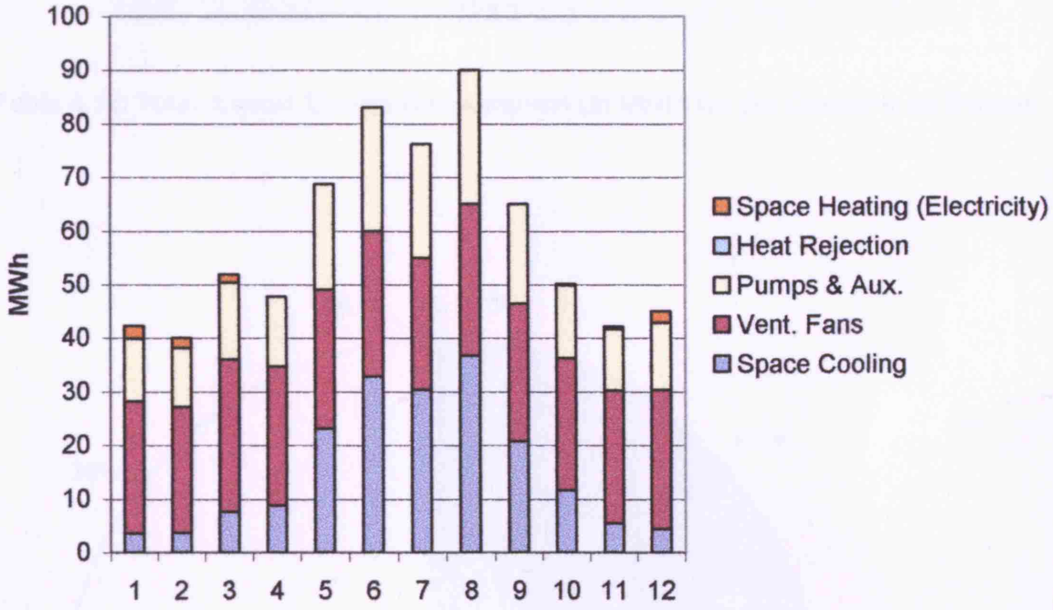


Figure 4.13: Monthly Electric Consumption (in MWh) for the Closed-loop System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Space Cooling	3.5	3.7	7.6	8.8	23.1	32.8	30.3	36.7	20.7	11.6	5.5	4.4
Heat Rejection	-	-	-	-	-	-	-	-	-	-	-	-
Space Heating	2.4	1.8	1.5	0	0	0	0	0	0	0.2	0.5	2.1
Vent. Fans	24.7	23.4	28.4	25.9	26	27.1	24.7	28.4	25.8	24.7	24.7	25.9
Pumps & Aux.	11.7	11.1	14.4	13	19.6	23.1	21.2	25	18.5	13.6	11.5	12.6
TOTAL	42.3	40	51.9	47.7	68.7	83	76.2	90.1	65	50.1	42.2	45

Table 4.11: Monthly Electric Consumption (in MWh) for the Closed-loop System

	Electricity (in MWh)	Natural Gas (in MWh)
Space Cooling	188.7	-
Heat Rejection	-	-
Space Heating	8.5	-
Vent. Fans	309.7	-
Pumps & Aux.	195.3	-
Total	702.2	-

Table 4.12: Total Annual Energy Consumption (in MWh) for the Closed-loop System

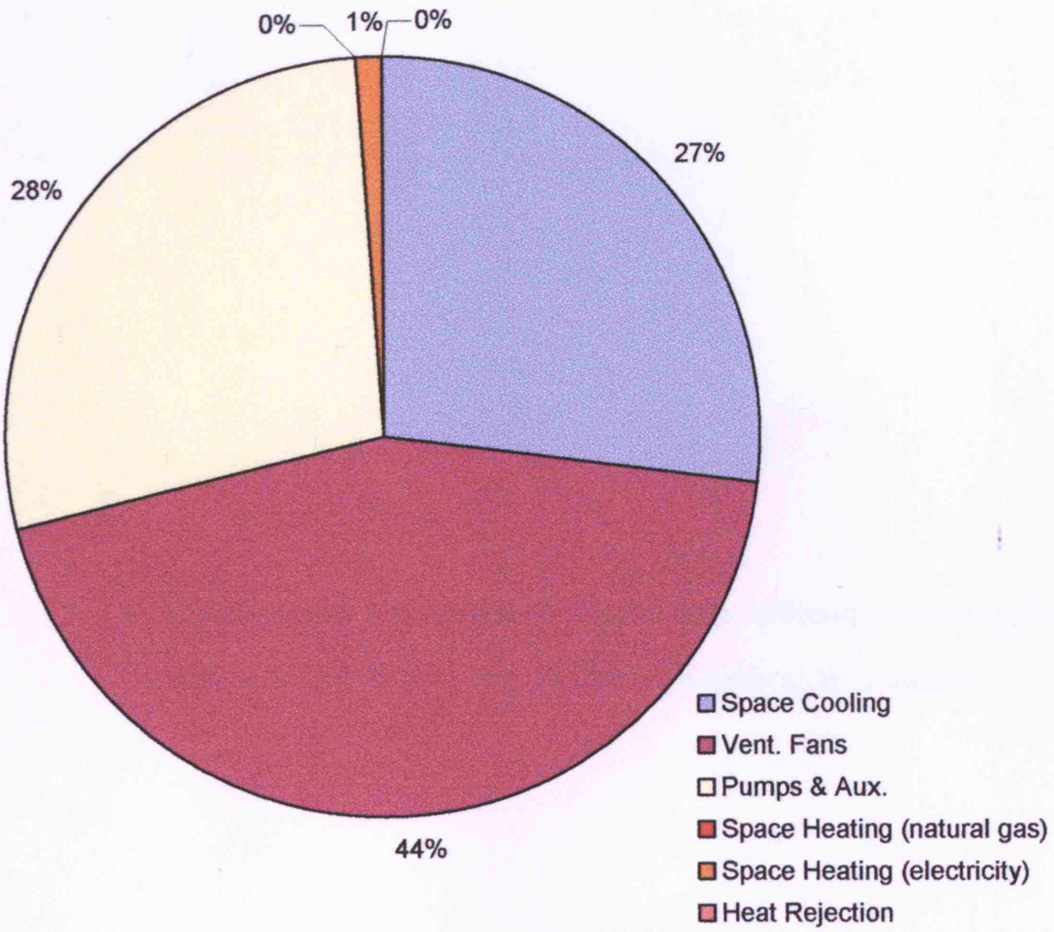


Figure 4.14: Total Annual Energy Consumption (in MWh) for the Closed-loop System

5. ANALYSIS OF RESULTS

5.1 Comparison of Simulations' Results in Terms of Energy Consumption

In the previous chapter simulations were performed for four different types of systems:

- Base model using a conventional variable air volume (VAV) air-conditioning with air-cooled water chillers and a gas boiler heating system.
- Base model using a WLHP system which includes a cooling tower and a gas boiler.
- Base model using a WLHP system combined with an open-loop SWHP system.
- Base model using a WLHP system combined with a closed-loop SWHP system.

Figure 5.1 presents annual energy consumption in MWh for activities that concern space heating, cooling and required pumping energy.

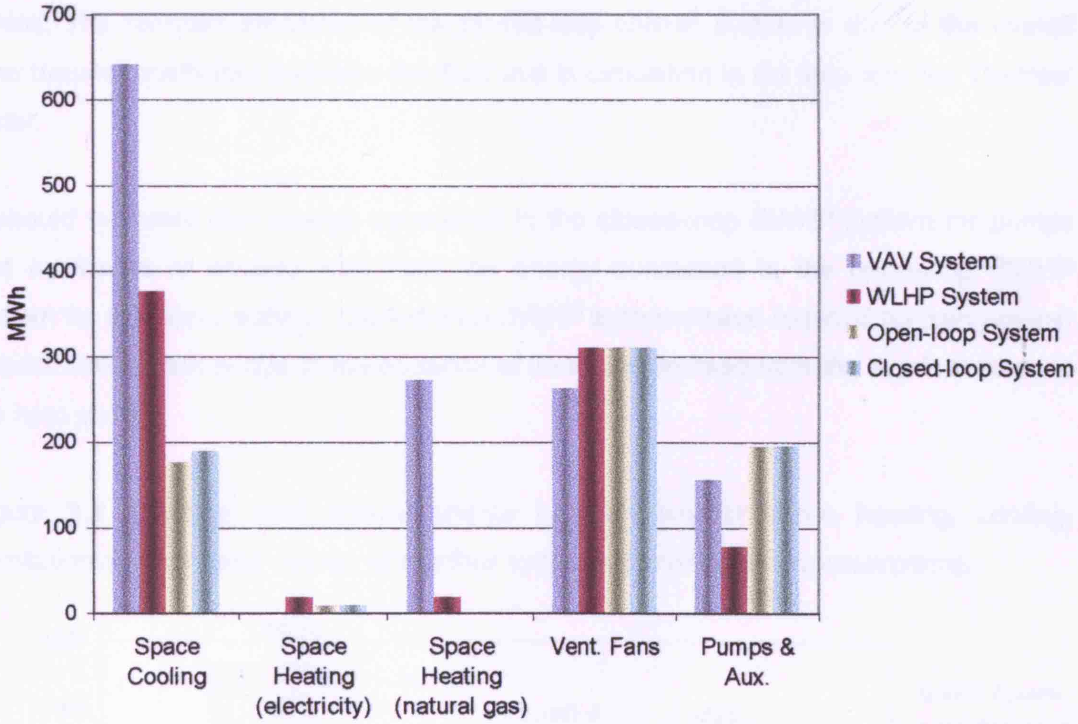


Figure 5.1: Annual Energy Consumption

It is therefore concluded that the most energy consuming system is the VAV air-conditioning system. The conventional WLHP system consumes less energy for space heating and cooling due to the operation of the heat pumps which can transfer heat from spaces that need cooling to spaces that need heating. Therefore the fluid cooler and the gas boiler of the WLHP system consume less energy than the VAV air-conditioning system though slightly more energy is consumed by the WLHP system for the ventilation fans.

The two SWHP systems, both the open-loop and the closed-loop consume almost half of the energy for space heating and cooling that the conventional WLHP system does. The WLHP system though has significantly less pumping energy consumption comparing to both SWHP systems.

Regarding the two SWHP systems, it is obvious that the open-loop SWHP system has a slightly better performance comparing to the closed- loop SWHP system in what concerns energy consumption for space cooling. This is occurring during the summer period. The reduced efficiency of the closed-loop SWHP system is due to the overall heat transfer coefficient between the fluid that is circulating in the loop and the Thames' water.

It should be noted that energy consumed in the closed-loop SWHP system for pumps and auxiliaries is actually less than the energy consumed in the open-loop SWHP system for the same activity. Closed-loop SWHP systems have reduced pumping-power requirement[1] which is due to the absence of an elevation head from the river's surface to the heat pumps.

Figure 5.2 presents total annual energy consumption for space heating, cooling, ventilation and pumping energy of the four systems (including gas consumption).

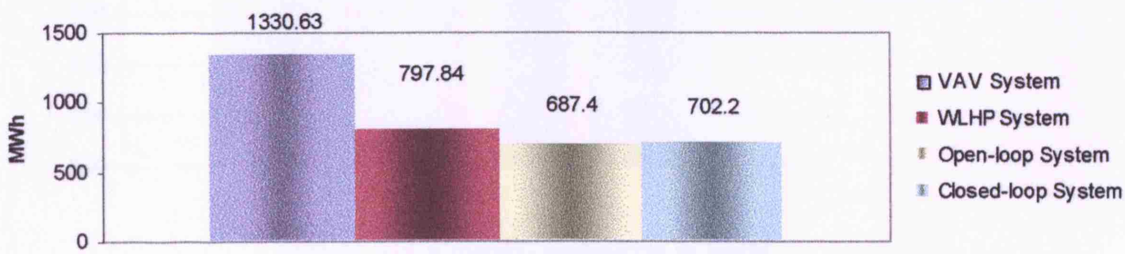


Figure 5.2: Total Annual Energy Consumption

[1] ASHRAE: HVAC Applications, SI Edition (2003).

5.2 Comparison of Simulations' Results in Terms of CO_2 Emissions

Energy consumed from buildings causes the emission of the so- called greenhouse gases with the major one being CO_2. Each kWh of delivered energy is responsible for the production of CO_2 emissions from the extraction, processing and delivery of each fuel and its consumption on site[2]. Table 5.1 presents conversion factors in C and CO2 per kWh of delivered type of fuel. It should be noted that the conversion factor for electricity varies with the primary fuel mix used to generate it.

FUEL	kgC/kWh	$kgCO_2/kWh$
Gas	0.052	0.19
Oil	0.069	0.25
Coal	0.081	0.30
Electricity (average)	0.127	0.46

Table 5.1: Conversion Factors in C and CO_2 per kWh of delivered type of fuel (Source: Digest of UK Energy Statistics 1999)

Taking the above into account, figure 5.3 presents annual emissions of C (in kg) for the four different systems per m².

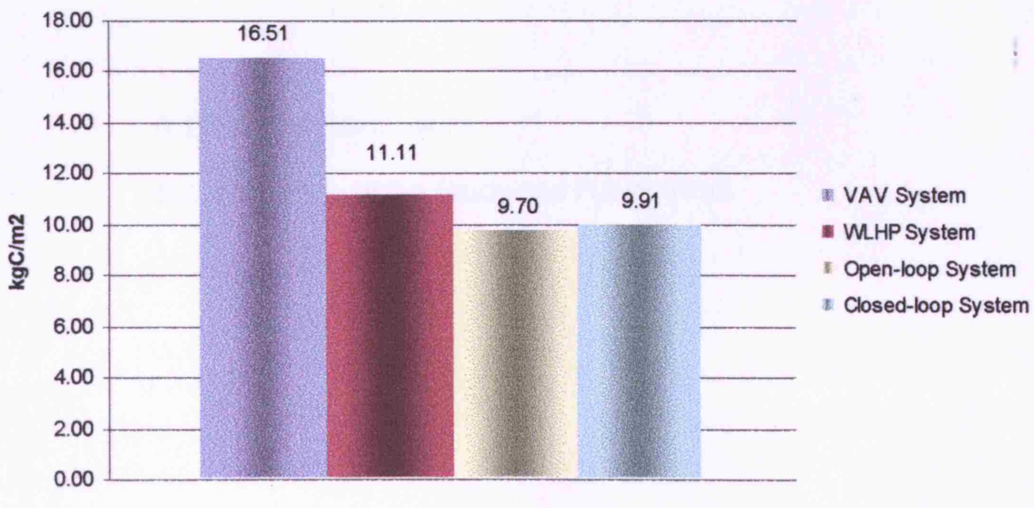


Figure 5.3: Annual C emissions in kg/m²

[2] The Government's Energy Efficiency Best Practice Programme: Energy Use in Offices, Energy Consumption Guide 19.

6. CONCLUSIONS

6.1 General Conclusions

The general concept of heat pump technology has always been considered an important step towards the development of more efficient HVAC systems. Office buildings often present simultaneous demands for heating and cooling in spring, autumn and even in winter which favours the use of a WLHP system. Taking this into account along with the fact that large bodies of water can potentially be used as a source or sink for a WLHP system, the prospect of using the Thames' water was examined.

This project focused on the energy performance of four different heating and cooling systems of a typical office building; a VAV central air-conditioning system, a WLHP system, an open-loop SWHP system and a closed-loop SWHP system. A life cycle cost analysis was beyond the scope of this study, however, payback periods are in favour of the SWHP systems due to their reduced operational and maintenance costs.

General conclusions of this study, as derived from the simulation results of the four systems as well as from the analysis of the Thames' characteristics, are summarised below:

- WLHP systems, including energy consumed for ventilation, are undoubtedly more efficient compared to VAV central air-conditioning systems, both in terms of energy consumption and CO_2 emissions, at least in buildings that present simultaneous demands for heating and cooling, which is common in office buildings. The particular case study showed that a WLHP system consumes approximately 60% of the energy consumed by a VAV central air-conditioning system while it produces 67% of its CO_2 emissions.
- Simulation results comparing a conventional WLHP system and an open-loop SWHP system showed that an open-loop SWHP system consumes 14% less energy than a conventional WLHP system, while it produces 13% less CO_2 emissions. Energy savings could be higher if there was less energy consumed for pumping in the case of the open-loop SWHP system. The open-loop SWHP system consumes 2.5 times the pumping energy consumed by a conventional WLHP system. This is due to the fact that a conventional WLHP system consumes energy in pumping only within the building while an open-loop SWHP system consumes energy to circulate water from the river as well.

- The power consumption of the pump is proportional to the distance and the elevation between the water source (in this case the Thames) and the system which is located in the building. Therefore, the feasibility of using water as a heat source – sink in SWHP systems depends on the distance and the elevation between the water source and the building. Taking into account the significant amounts of energy that are consumed for pumping, the location of the buildings should be as close as possible to the Thames.
- As analysed in Section 3.5, the most feasible system in the case of the Thames appears to be a closed- loop SWHP system due to the reduced fouling resulting from the circulation of clean water (or water-antifreeze solution) instead of the direct circulation of the Thames water which would also raise environmental concerns. Furthermore, closed-loop systems are the only type recommended for water temperatures below 5.0 °C which is a possibility in the case of the Thames.
- Simulation results showed that a closed-loop SWHP system consumes 12% less energy than a conventional WLHP system, while it produces 11% less CO_2 emissions. Obviously, results are slightly less promising that the results of the open-loop SWHP system. As previously mentioned however (Section 5.1), energy consumed in the closed-loop SWHP system for pumps and auxiliaries is actually less than the energy consumed in the open-loop SWHP system for the same activity. Therefore it can be assumed that the overall performance of the open-loop and the closed-loop SWHP system is practically the same.

In conclusion, this study showed that a reduction of more than 10% in energy consumption and CO_2 emissions was achieved with the use of a closed-loop SWHP system. Therefore closed-loop SWHP systems are an energy efficient practice in office buildings adjacent to the Thames. The capital cost of this system however is higher than the cost of a conventional system due to the installation of the river coils. Despite the fact that the system has a reasonable payback period, the building industry's common practice is to aim for a lower initial cost since operating costs will be handled by the tenants. Taking these points into consideration, government intervention or funding would significantly contribute towards the realisation of such a scheme.

6.2 Limitations of the Study and Future Work

The basic limitation of this study was the lack of appropriate simulation software, able to simulate directly closed-loop SWHP systems as well as hybrid SWHP systems (systems that use downsized cooling towers). A further study on the performance of hybrid[1] SWHP systems would be extremely useful since these systems have river coils of reduced size and therefore reduced capital cost. The river coils would be sized to meet the total heating demands of the building, which are significantly less than its cooling demands and part of its cooling demands. This would also lead to reduced pumping energy. Since the river coil of the SWHP system would not be able to meet the total cooling load a downsized cooling tower would be added to the loop.

Additionally, future study could be focused on life cycle cost analysis of SWHP systems as well as on sensitivity tests regarding the distance of the building from the heat source/sink, the height of the building and the optimum temperature range of the heat source/sink depending on the building's loads.

Furthermore, there are several European cities situated near large rivers or the sea, as Paris, Amsterdam, and Prague. The feasibility of the use of these water volumes as a source/sink for SWHP systems depends on the buildings' distance from the source/sink, the thermal characteristics of the water volumes and how these characteristics respond to the local climate. A future study into the above would be extremely useful, taking into account the high energy consumption of commercial buildings in urban centers. The installation of efficient SWHP systems would lead to significant energy savings and reduction in CO_2 emissions, especially if it involved the development of large schemes.

[1] Kavanaugh SP: Ground- coupling with Water Source Heat Pumps, The University of Alabama (1991).

1. ASHRAE: Applied Heat Pump Opportunities in Commercial Buildings (1989).
2. ASHRAE: Operating Experiences with Commercial Ground Source Heat Pump Systems (1998).
3. ASHRAE Applications Handbook: Geothermal Energy (2003).
4. ASHRAE: HVAC Applications, SI Edition (2003).
5. Assessment of Hybrid Geothermal Heat Pump Systems: U.S. Department of Energy (2001).
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7. CIBSE Building Energy Code 2: Energy Demands for Air-Conditioned Buildings (1999).
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9. CIBSE Guide B2: Ventilation and Air- Conditioning (2001).
10. Doug Cane & Jeremy Garnet: Commercial/Institutional Heat Pump Systems in Cold Climates (2000).
11. Ground Source Heat Pumps Seminar: The National Energy Foundation (2005).
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13. Kavanaugh SP: Lakewater applications of water to air heat pumps, ASHRAE (1990).
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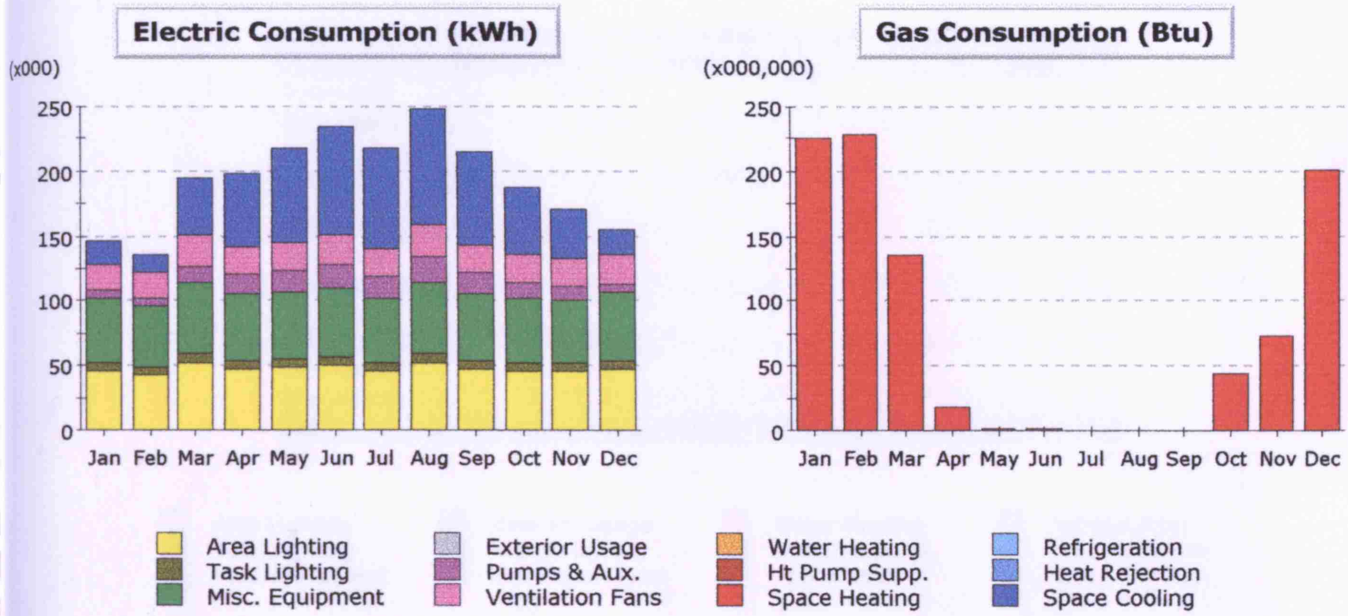
16. Natural Resources Canada/Energy Publications: Heating and cooling with a heat pump: (2000).
17. Natural Resources Canada/Energy Publications: Commercial Earth Energy Systems (2002).
18. Pout C.H., Moss S.A. and Davidson P.J.:Non-Domestic Building Energy Fact File (1998).
19. R.H.D. Rawlings: Ground Source Heat Pumps- A Technology Review (1999).
20. The Government's Energy Efficiency Best Practice Programme: Energy Use in Offices, Energy Consumption Guide 19.

APPENDIX A: EQUEST Spreadsheets



Electric Consumption (kWh x000)

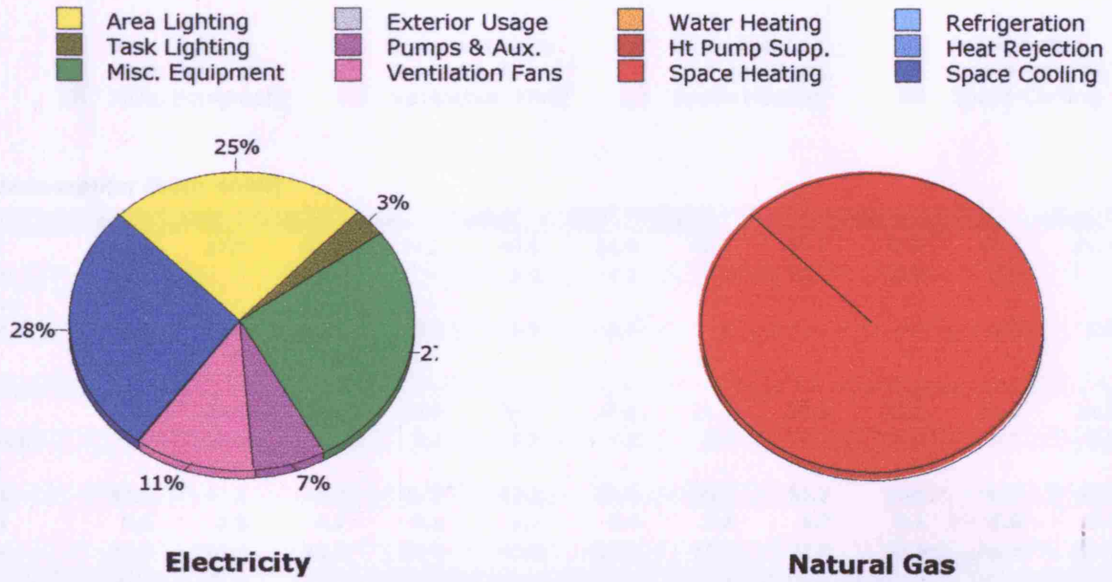
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	17.3	14.7	44.4	56.2	73.7	84.2	78.9	90.5	71.8	51.4	37.2	21.1	641.6
Heat Reject.	-	-	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	-	-	0.1
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	20.9	19.8	24.0	21.9	22.0	23.0	20.9	24.0	21.9	20.9	20.9	21.9	262.2
Pumps & Aux.	5.8	5.5	11.9	14.2	16.6	18.3	16.8	19.4	16.2	13.0	10.6	6.8	155.1
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	50.3	47.1	55.7	51.7	52.2	53.5	50.3	55.7	51.6	50.3	49.8	52.1	620.4
Task Lights	5.8	5.5	6.7	6.1	6.1	6.4	5.8	6.7	6.1	5.8	5.8	6.1	73.2
Area Lights	45.7	43.4	52.3	47.9	48.0	50.1	45.7	52.3	47.8	45.7	45.7	47.9	572.5
Total	145.9	136.1	195.1	198.0	218.6	235.4	218.5	248.8	215.4	187.2	170.1	156.1	2,325.1

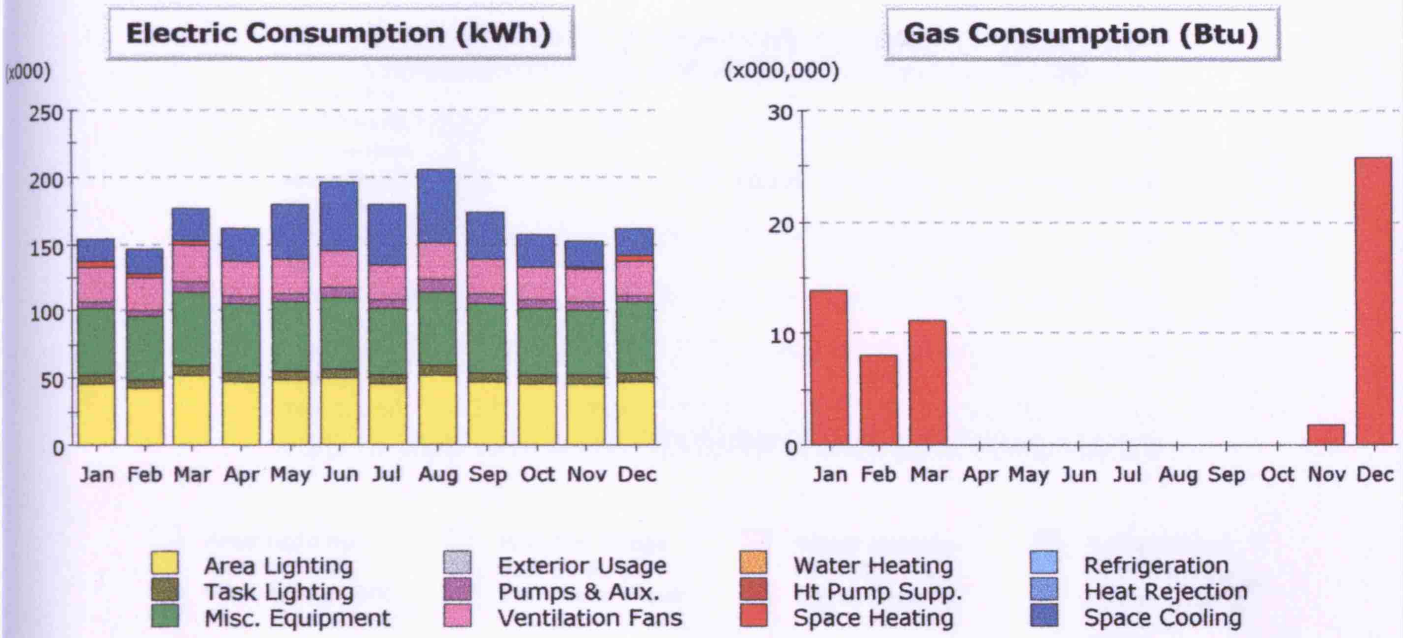
Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	225.37	227.96	135.47	18.41	1.37	0.89	-	-	-	43.75	72.90	201.27	927.37
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	225.37	227.96	135.47	18.41	1.37	0.89	-	-	-	43.75	72.90	201.27	927.37

Annual Energy Consumption by Enduse

	Electricity kWh (x000)	Natural Gas MBtu	Steam Btu	Chilled Water Btu
Space Cool	641.6	-	-	-
Heat Reject.	0.1	-	-	-
Refrigeration	-	-	-	-
Space Heat	-	927.37	-	-
HP Supp.	-	-	-	-
Hot Water	-	-	-	-
Vent. Fans	262.2	-	-	-
Pumps & Aux.	155.1	-	-	-
Ext. Usage	-	-	-	-
Misc. Equip.	620.4	-	-	-
Task Lights	73.2	-	-	-
Area Lights	572.5	-	-	-
Total	2,325.1	927.37	-	-





lectric Consumption (kWh x000)

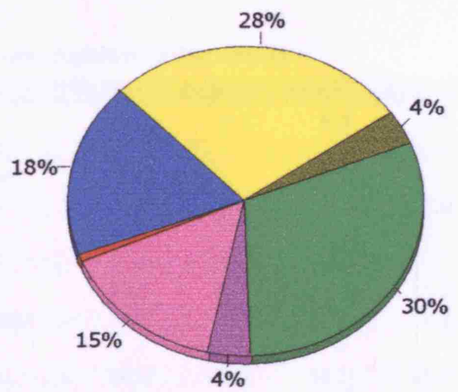
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	To
Space Cool	17.6	17.9	24.6	24.2	40.6	51.0	45.7	54.7	35.8	24.5	19.6	19.2	3
Heat Reject.	-	-	0.0	-	0.0	0.1	0.1	0.1	0.0	0.0	-	-	
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	
Space Heat	4.8	4.0	3.0	0.1	0.0	0.0	-	-	-	0.4	1.2	4.3	
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	
Vent. Fans	24.7	23.4	28.4	25.9	26.0	27.1	24.7	28.4	25.8	24.7	24.7	25.9	3
Pumps & Aux.	5.4	5.2	6.4	6.2	7.1	7.7	7.0	8.2	6.8	6.1	5.8	5.3	
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	
Misc. Equip.	50.3	47.1	55.7	51.7	52.2	53.5	50.3	55.7	51.6	50.3	49.8	52.1	6
Task Lights	5.8	5.5	6.7	6.1	6.1	6.4	5.8	6.7	6.1	5.8	5.8	6.1	
Area Lights	45.7	43.4	52.3	47.9	48.0	50.1	45.7	52.3	47.8	45.7	45.7	47.9	5
Total	154.2	146.6	177.2	162.0	180.0	195.9	179.3	206.2	173.9	157.6	152.6	161.0	2,

as Consumption (Btu x000,000)

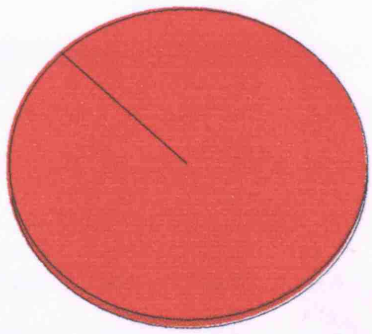
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	To
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	
Space Heat	13.92	7.98	11.20	-	-	-	-	-	-	-	1.75	25.71	[illegible]
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	
Total	13.92	7.98	11.20	-	-	-	-	-	-	-	1.75	25.71	[illegible]

Annual Energy Consumption by Enduse

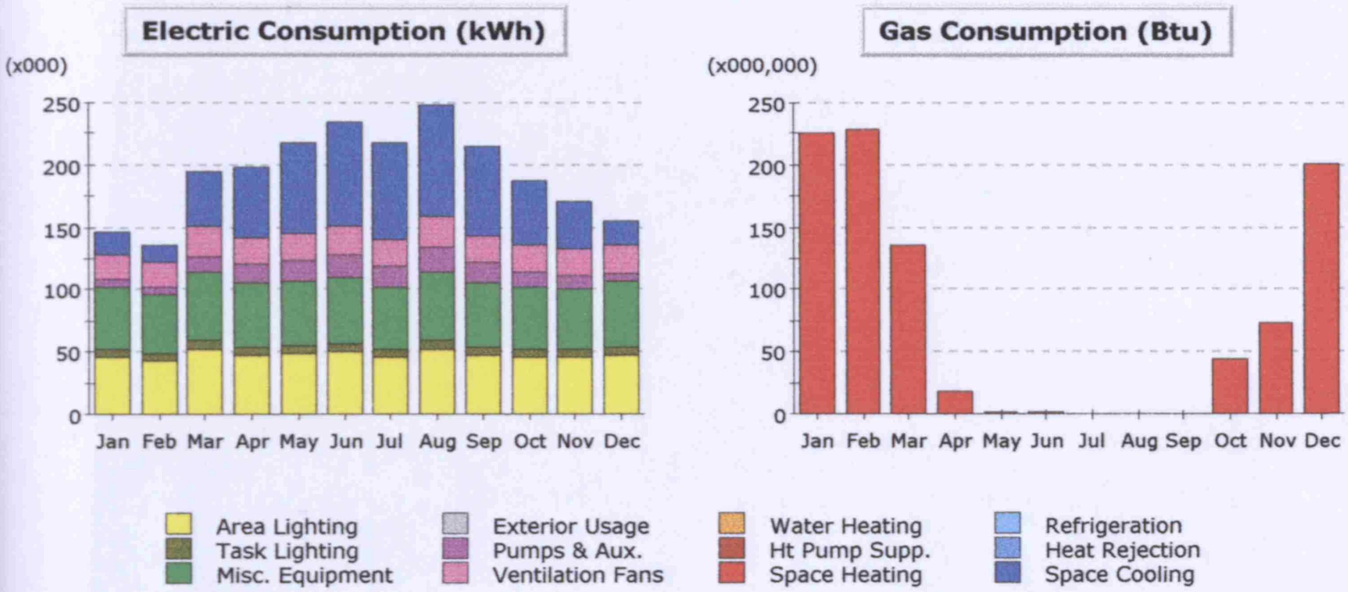
	Electricity kWh (x000)	Natural Gas Btu (x000)	Steam Btu	Chilled Water Btu
Space Cool	375.5	-	-	-
Heat Reject.	0.4	-	-	-
Refrigeration	-	-	-	-
Space Heat	17.7	60,560	-	-
HP Supp.	-	-	-	-
Hot Water	-	-	-	-
Vent. Fans	309.6	-	-	-
Pumps & Aux.	77.3	-	-	-
Ext. Usage	-	-	-	-
Misc. Equip.	620.4	-	-	-
Task Lights	73.2	-	-	-
Area Lights	572.5	-	-	-
Total	2,046.6	60,560	-	-



Electricity



Natural Gas



Electric Consumption (kWh x000)

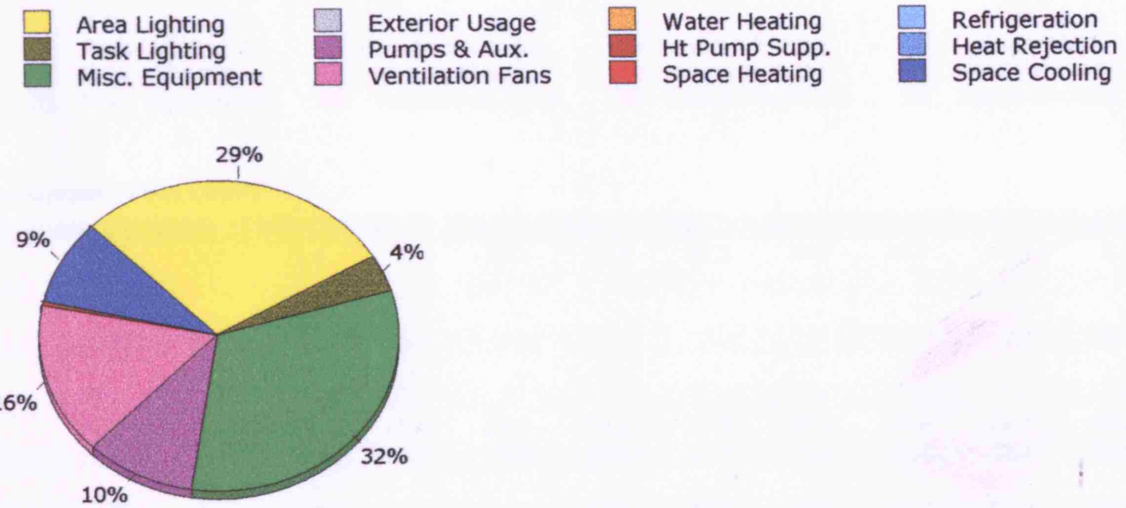
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	17.3	14.7	44.4	56.2	73.7	84.2	78.9	90.5	71.8	51.4	37.2	21.1	641.6
Heat Reject.	-	-	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	-	-	0.1
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	20.9	19.8	24.0	21.9	22.0	23.0	20.9	24.0	21.9	20.9	20.9	21.9	262.2
Pumps & Aux.	5.8	5.5	11.9	14.2	16.6	18.3	16.8	19.4	16.2	13.0	10.6	6.8	155.1
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	50.3	47.1	55.7	51.7	52.2	53.5	50.3	55.7	51.6	50.3	49.8	52.1	620.4
Task Lights	5.8	5.5	6.7	6.1	6.1	6.4	5.8	6.7	6.1	5.8	5.8	6.1	73.2
Area Lights	45.7	43.4	52.3	47.9	48.0	50.1	45.7	52.3	47.8	45.7	45.7	47.9	572.5
Total	145.9	136.1	195.1	198.0	218.6	235.4	218.5	248.8	215.4	187.2	170.1	156.1	2,325.1

Gas Consumption (Btu x000,000)

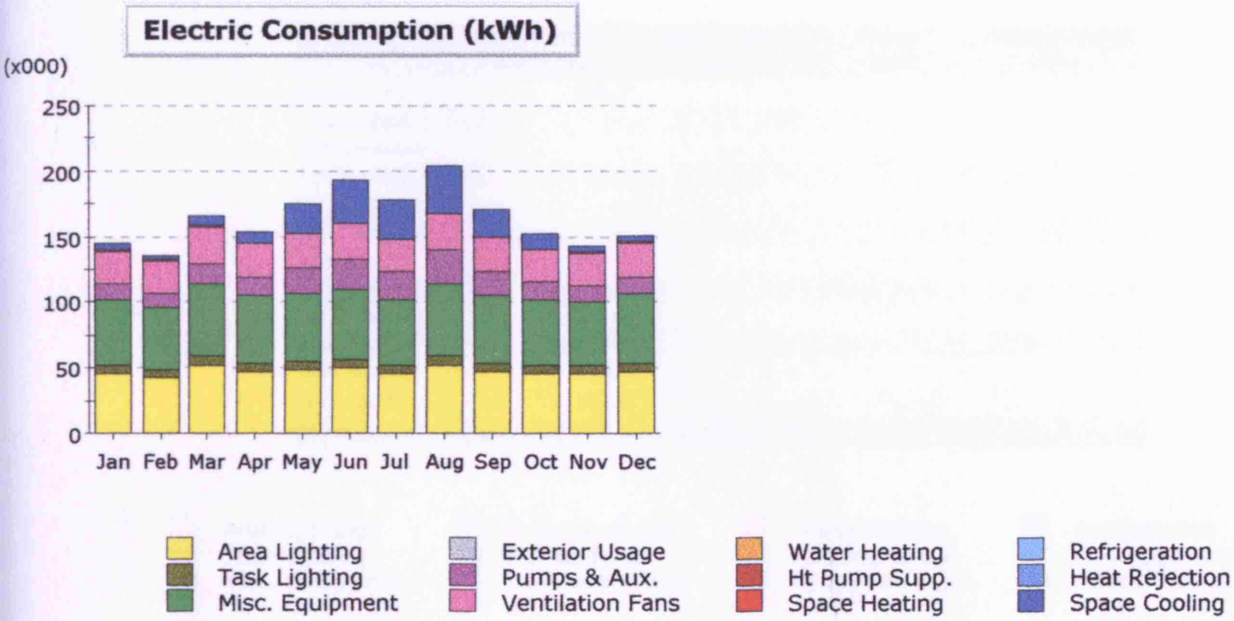
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	225.37	227.96	135.47	18.41	1.37	0.89	-	-	-	43.75	72.90	201.27	927.37
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	225.37	227.96	135.47	18.41	1.37	0.89	-	-	-	43.75	72.90	201.27	927.37

Annual Energy Consumption by Enduse

	Electricity kWh (x000)	Natural Gas Btu	Steam Btu	Chilled Water Btu
Space Cool	175.7	-	-	-
Heat Reject.	-	-	-	-
Refrigeration	-	-	-	-
Space Heat	8.2	-	-	-
HP Supp.	-	-	-	-
Hot Water	-	-	-	-
Vent. Fans	309.5	-	-	-
Pumps & Aux.	193.6	-	-	-
Ext. Usage	-	-	-	-
Misc. Equip.	620.4	-	-	-
Task Lights	73.2	-	-	-
Area Lights	572.5	-	-	-
Total	1,953.2	-	-	-



Electricity



Electric Consumption (kWh x000)

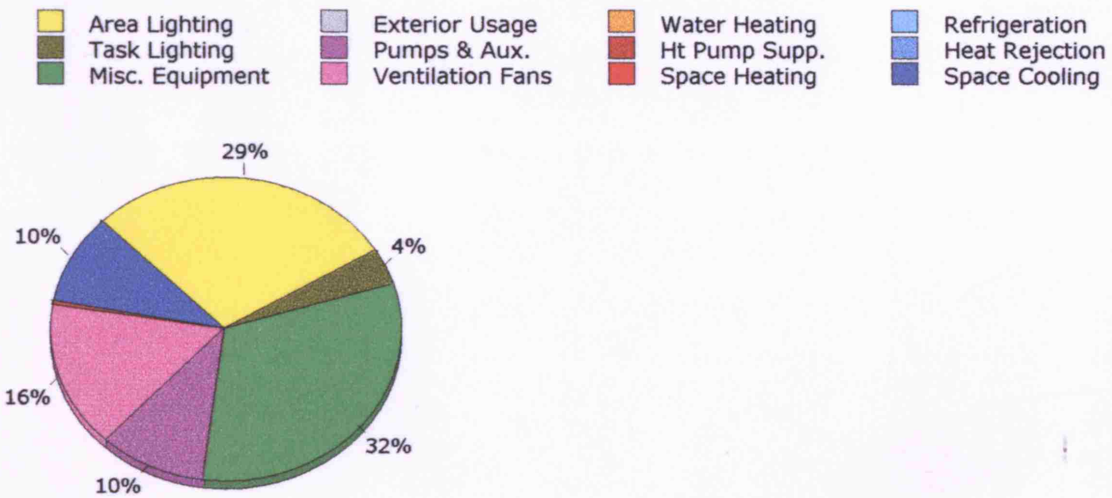
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	3.5	3.7	7.6	8.8	23.1	32.8	30.3	36.7	20.7	11.6	5.5	4.4	188.7
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	2.4	1.8	1.5	0.0	0.0	-	-	-	-	0.2	0.5	2.1	8.4
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	24.7	23.4	28.4	25.9	26.0	27.1	24.7	28.4	25.8	24.7	24.7	25.9	309.5
Pumps & Aux.	11.7	11.1	14.4	13.0	19.6	23.1	21.2	25.0	18.5	13.6	11.5	12.6	195.3
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	50.3	47.1	55.7	51.7	52.2	53.5	50.3	55.7	51.6	50.3	49.8	52.1	620.4
Task Lights	5.8	5.5	6.7	6.1	6.1	6.4	5.8	6.7	6.1	5.8	5.8	6.1	73.2
Area Lights	45.7	43.4	52.3	47.9	48.0	50.1	45.7	52.3	47.8	45.7	45.7	47.9	572.5
Total	144.1	136.0	166.7	153.3	175.0	193.0	178.1	204.8	170.6	151.8	143.5	151.1	1,968.0

Gas Consumption (Btu)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject.													
Refrigeration													
Space Heat													
HP Supp.													
Hot Water													
Vent. Fans													
Pumps & Aux.													
Ext. Usage													
Misc. Equip.													
Task Lights													
Area Lights													
Total													

Annual Energy Consumption by Enduse

	Electricity kWh (x000)	Natural Gas Btu	Steam Btu	Chilled Water Btu
Space Cool	188.7	-	-	-
Heat Reject.	-	-	-	-
Refrigeration	-	-	-	-
Space Heat	8.4	-	-	-
HP Supp.	-	-	-	-
Hot Water	-	-	-	-
Vent. Fans	309.5	-	-	-
Pumps & Aux.	195.3	-	-	-
Ext. Usage	-	-	-	-
Misc. Equip.	620.4	-	-	-
Task Lights	73.2	-	-	-
Area Lights	572.5	-	-	-
Total	1,968.0	-	-	-



Electricity

APPENDIX B: Comparison of Results to ECON 19

Comparison of Results to ECON 19[1]

ECON 19 is an "energy consumption guide intended to raise awareness of the potential to improve the energy and environmental performance of offices and to encourage positive management action". The guide describes four types of office buildings and their performance regarding energy consumption against which the performance of any office building can be compared.

This Guide gives benchmarks for "typical" energy consumption patterns as well as for "good practise" energy consumption patterns in which significantly lower energy consumption has been achieved using energy-efficient features and management practices.

The generic type of office building that best responds to this project's building is type 3, the air-conditioned standard office building. According to ECON 19 this a largely purpose-built with a typical size ranging from 2000 m² to 8000 m². The benchmarks are based on variable air volume (VAV) air-conditioning with air-cooled water chillers.

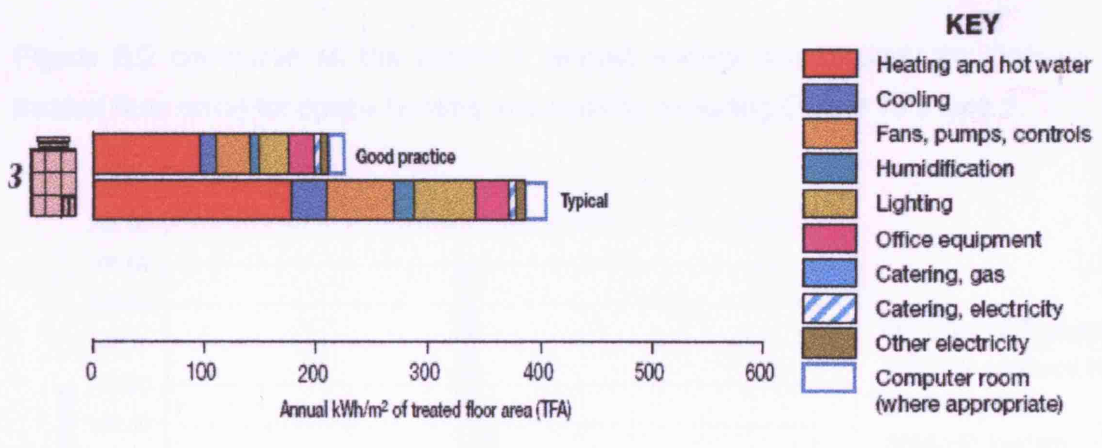


Figure B.1: Annual Energy Use in ECON 19

Figure B.1 presents annual energy use indices in KWh/ m² of treated floor area, according to ECON 19 for both typical and good practice patterns Table B.1 presents in tabular form the data of the previous figure, thus annual consumption of good practice and typical offices for the third office type (in kWh/m² of treated floor area).

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[1] The Government's Energy Efficiency Best Practice Programme: Energy Use in Offices, Energy Consumption Guide 19.

	3	
	Good practice	*Typical*
Heating and hot water – gas or oil	97	178
Cooling	14	31
Fans, pumps, controls	30	60
Humidification (where fitted)	8	18
Lighting	27	54
Office equipment	23	31
Catering, gas	0	0
Catering, electricity	5	6
Other electricity	7	8
Computer room (where appropriate)	14	18
Total gas or oil	97	178
Total electricity	128	226

Table B.1: Annual Energy Use in ECON 19

Figure B.2 compares all the systems' annual energy consumption (in kWh/m² of treated floor area) for space heating and cooling, including ECON 19's type 3.

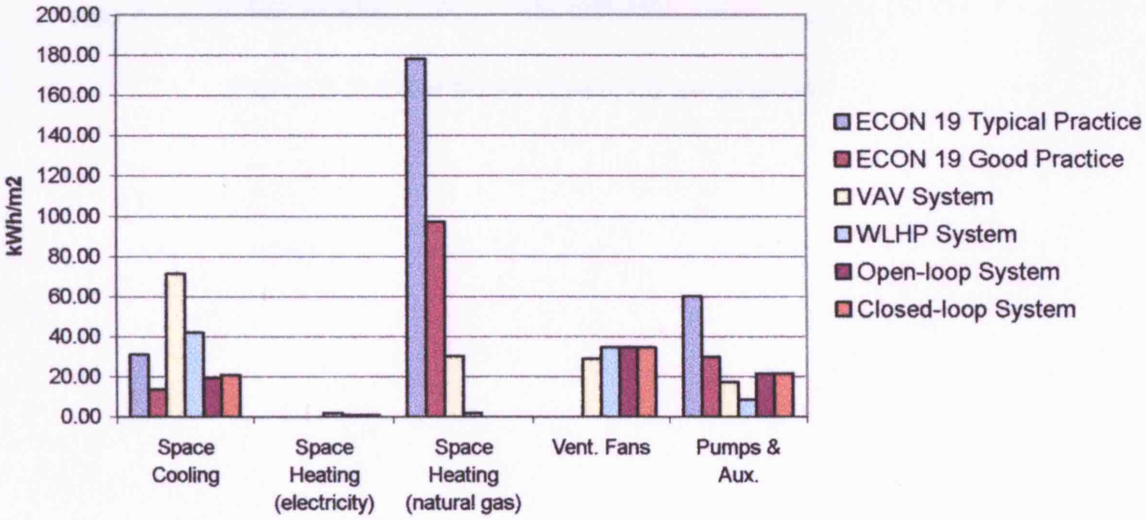

Figure B.2: Annual Energy Consumption

An increased difference is noticed in energy consumption for space heating in ECON 19's results. ECON 19 takes into account hot water energy consumption as well but still the difference is significant.

Figure B.3 presents total annual energy consumption for space heating, cooling, ventilation and pumping energy. It can be noticed that the WLHP system as well as both SWHP systems consume significantly less energy from the ECON 19's Good Practice.

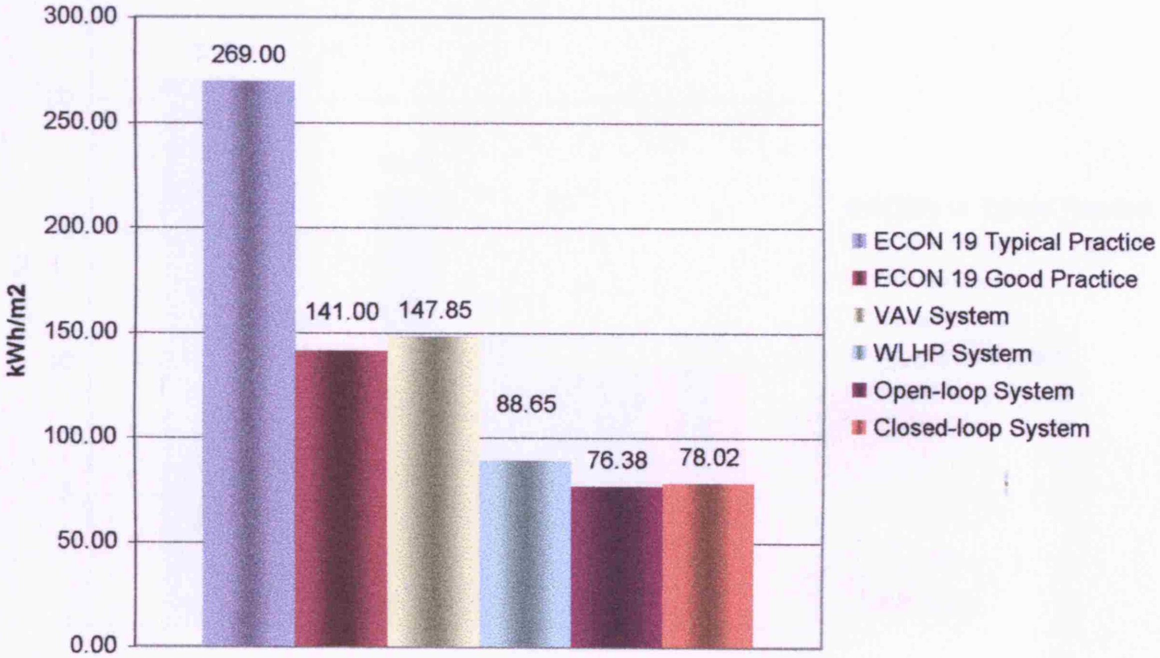

Figure B.3: Total Annual Energy Consumption

Figure B.4 presents annual emissions of C (in kg per m²) due to energy consumption for space heating, cooling, ventilation and pumping energy. It is noticed that the previous difference in energy consumption does not lead to the same difference in C emissions. This is due to the fact that ECON 19's case studies consume higher amounts of gas in comparison to electricity. Electricity accounts for 0.127 kgC per kWh of delivered energy while on the other hand gas accounts for 0.052 kgC per kWh of delivered energy, which is more than a 50% reduction in C emissions.

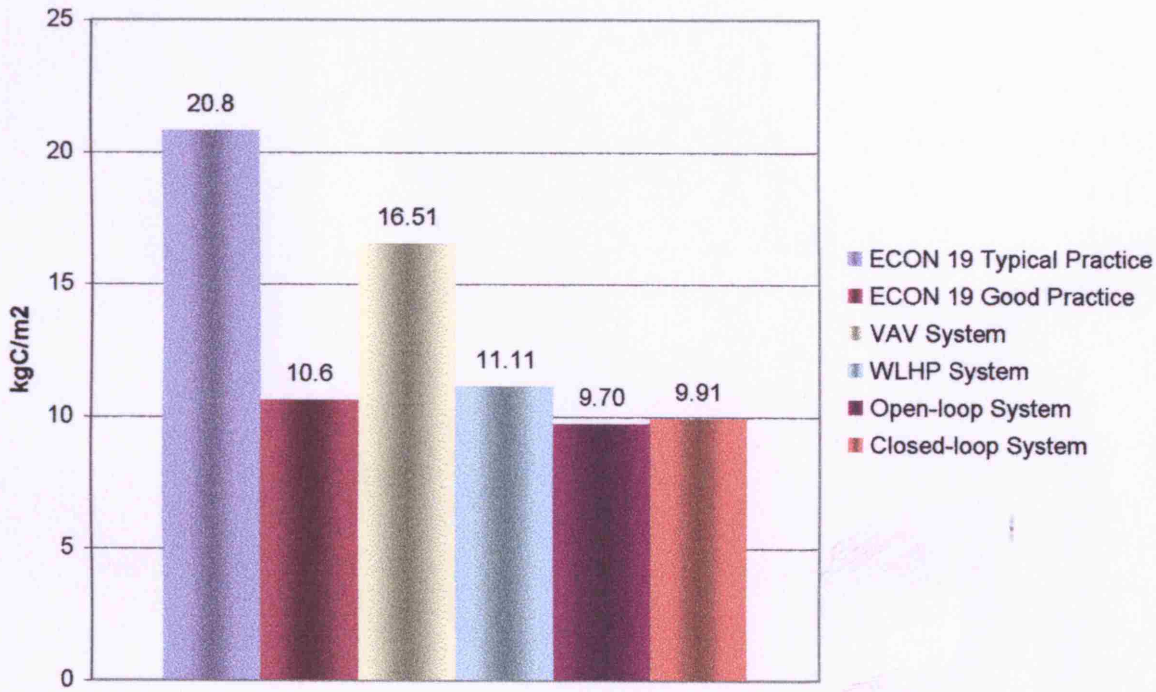

Figure B.4: Annual C Emissions in kg/m²